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14. ABSTRACT

The AFOSR MURI "Explosive-Driven Power Generation to Directed-Energy Munitions" started in May 1998. The two year option was exercised and a no-cost extension until April 2003 was granted. This report summarizes the activities of the university partners (Texas Tech University, University of Missouri-Rolla, and Texas A&M University. The consortium research staff consists of faculty, postdoctoral fellows, and graduate students from the three universities and involves the departments of Electrical Engineering, Physics, Mechanical Engineering, Mining Engineering, and Nuclear Engineering. The research objectives were to obtain improved basic understanding of the fundamental processes in Magnetic Flux Compression Generators and to develop high efficiency power conditioning techniques for matching the MFGG output to directed energy generator loads. The basic information obtained should aid in designing future compact, high efficiency power sources for directed energy munitions. A handbook based on this research is being finalized.

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Introduction

The Department of Defense with AFOSR as their contracting Agency awarded a Multidisciplinary University Research Initiative (MURI) grant to further explore the possibilities of producing efficient "Explosive-Driven Power Generation for Directed-Energy Munitions" on 1 May 1998. A two-university consortium consisting of Texas Tech University (TTU) and the University of Missouri at Rolla (UMR) received this grant. Texas A&M University was added as a third consortium member in September 1998, and The University of Texas was a participant for a short period of time. The two year option of the program was exercised and a no-cost extension until 9-30-03 was granted.

This progress report summarizes and describes the division of work, goals, and the research activities that took place. The principal investigators at each institution are:

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Completed work in July 2000. The University of Texas' contribution in this report period produced two papers based on their completed work that was reported in a previous annual progress report.

I. PERSONNEL AT TEXAS TECH UNIVERSITY

Professor M. (Kris) Kristiansen, Principal Investigator and Consortium Director

Task

1. Research on Power Conditioning Using C4 driven MFCGs.
   - Associate Prof. M. Giesselmann and Associate Prof. J. Dickens (Direct theoretical and laboratory research)
   - Tammo Heeren, graduate student (Conducts laboratory research) (Design of basic power conditioning system)

2. Thermodynamic State of the Trapped Gas Between Armature and Stator of Flux Compression Generators
   - Assistant Prof. A. Neuber and Prof. H. Krompholz (Direct laboratory research)
   - David Hemmert, graduate student (Conducts laboratory research)
   - Thomas Holt, graduate student (Conducts laboratory research)

3. Impact of Helix Geometry on Generator Performance
   - Prof. A. Neuber (Directs laboratory research)
   - Thomas Holt, graduate student (Conducts laboratory research)
   - Nathan Schoeneberg, graduate student (Conducts numerical simulations)
   - Juan Carlos Hernandez, Ph.D student (numerical simulation, lab research)

4. Effect of "Scaling" on the Armature Expansion Angle in an MFCG
   - Prof. J. Rasty (Directs theoretical and laboratory research)
   - X. Le, doctoral candidate (Conducts laboratory and theoretical research)

5. Finite Element Simulation of the Stator Wire Impacted by the Armature in an MFCG
   - Prof. J. Rasty (Directs theoretical and laboratory research)
   - X. Le, doctoral candidate (Conducts numerical simulation research)

II. PERSONNEL AT THE UNIVERSITY OF MISSOURI -ROLLA

- Prof. Paul N. Worsey, Principal Investigator and Director of Laboratory Research
- Jason Baird, awarded Ph.D. degree, August 2001.
- Mark Schmidt, graduate student in Mining Engineering pursing Ph.D. degree (Intends Ph.D. research to be an extension of Dr. Baird's dissertation work.)

Task

1. Energetic materials studies and tests
   - Jason Baird (Conducts laboratory research)
   - Mark Schmidt (Conducts laboratory research)

2. Comparison of numerical modeling to test data.
   - Jason Baird (Conducts laboratory research)
   - Mark Schmidt (Conducts laboratory research)

III. PERSONNEL AT TEXAS A&M UNIVERSITY

Dr. Bruce L. Freeman, P.I. (Directs theoretical and laboratory research)
J. C. Rock, Faculty member
A. D. Luginbill, Research Engineer
John Boydston, Masters Graduate Student
Teresa Tutt, Ph.D. Graduate Student

Task

1. Simultaneous Generator Design
   - Dr. Bruce L. Freeman
   - Dr. James C. Rock
   - Dr. Marcus A. Cash (Eglin AFB)
   - Dr. Steve Hallett (PANTEX)

2. Small Generator Design and Testing
   - Dr. Bruce L. Freeman
   - Dr. James C. Rock
   - Dr. Larry L. Altgilbers (SMDC)
   - John Boydston

EXECUTIVE SUMMARY

The MURI Explosive-Driven Power Generation for Directed-Energy Munitions was awarded to Texas Tech University with the University of Missouri at Rolla on 6/3/98. The two year option was funded and a no-cost extension was approved from 5/1/03 to 9/30/03. Texas A&M University was added as a 3rd partner on 9/23/98. Initially the actual explosives tests were all done at the UMR (University of Missouri-Rolla) Explosive Laboratory. Later both TTU (Texas Tech University) and TAMU (Texas A&M University) developed their own explosives facilities. For a short time The Institute for Advanced Technology at The University of Texas at Austin was involved by using some of their computer codes to calculate magnetic field diffusion in the armatures.

The overall objectives of this program had two major parts:

1. Determine the effect of the various physical parameters and their required accuracies on the design and construction of explosive, compact, helical, flux compression generators.
2. Investigate methods for changing the high current (MA), low voltage (kV) output from helical flux compression generators to currents (10's kA) and voltages (100's kV) suited to drive loads, such as high power microwave devices.

The interaction between the 3 universities was extensive, e.g. TTU conducting its initial experiments at UMR and UMR continuing the study of armature behavior for TTU designs. Interactions with various government and industrial organizations were also extensive, e.g. TTU and TAMU delivering a large number of generators to NAVAIR at China Lake, CA on subcontracts.

A wide range of parameters were investigated. These included generator dimensions, geometry, materials, parameter sensitivities (e.g. alignment requirements), opening switch parameters (fuse wire dimensions, materials, etc.) and system integration.

The overall results of all these investigations are described in a Handbook on Helical Magnetic Flux Compression Generators, which is due to be published in 2004.

The following academic departments were involved in this program: Electrical and Computer Engineering, Mechanical Engineering, Nuclear Engineering, Mining Engineering, and Physics.

A summary of the program together with a list of publications and graduate students are included.

PROGRAM DESCRIPTION

Each of the four universities has specialized knowledge and capabilities that are essential to the success of the program. Texas Tech's expertise is in the areas of pulsed power, plasma and pulsed power diagnostics, and metallurgy, the University of Missouri at Rolla has explosive facilities and handling capabilities, Texas A&M University has past experience with Magnetic Flux Compression Generators and also an explosives facility. The University of Texas has available special computer codes that can be applied to study current flow and magnetic flux diffusion in MCG's. Magnetic Flux Compression Generators are very inefficient in converting the explosive energy into electrical energy, typically less than 10%. Their output is also unsuitable for driving directed energy sources. The MFCG is typically in the MA, 10's kV, 10 μs range whereas high power microwave sources typically require 10's kA, 100's kV, 1 μs type pulses. The power conditioning processes that have been attempted for matching the MFCG to the loads are also usually very inefficient, resulting in an overall system efficiency of, at best, a few percent. In order to improve the overall system efficiency, it is important to understand the basic loss mechanisms in the FMCG's and to develop improved power conditioning techniques. The overall goal of this MURI program is to develop the basic information and techniques to enable future designs of compact, high efficiency systems.

Each university in the consortium has its own specific research areas and goals. The overall program is basic (6.1) and is aimed at developing knowledge, understanding, and techniques that will be useful for developing improved explosive-driven power generators. Obvious examples are:

1. How to identify the loss mechanisms in flux compression generators in order to design them from first principles, and

2. How to condition the typically high current, low voltage (100's kA, 10's kV) output pulses to higher voltage, lower current pulses (10's kA, 100's kV).

Fundamentals of Magnetic Flux Compression Generators

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Abstract— Magnetic Flux Compression Generators offer the largest pulsed power output per unit size or weight, when compared with other more conventional systems. They have found widespread use, as pulsed power sources for hydrodynamics programs and high magnetic field research at national laboratories, or in commercial applications including exploration for oil and minerals, and mine detection. Also, due to their nature as a true one-time use device with superior energy density, a large portion of applications is defense related. The most successful basic design is the helical flux compression generator, which is capable of producing a high-energy output into large impedance loads, just as it is needed for a practical pulsed power source. We will briefly discuss in the following the fundamentals of helical magnetic flux compression generators.

A. **Flux Compression Principle, Ideal Generator and Real World**

The basic idea for producing a high magnetic field or a pulsed power output with a flux compression generator is simple: (1.) Magnetic flux is established in a system of conductors arranged such they trap the magnetic flux. (2.) The system of conductors is explosively deformed to a smaller volume thus compressing the flux and pushing electromagnetic energy into the connected load. The initial or seed flux can be established by a permanent or pulsed magnetic field utilizing either permanent magnets or a current-pulsed seed inductance fed, for instance, by a small capacitor bank.

The phases of operation for a simple helical flux compression generator are depicted in Fig. 1.

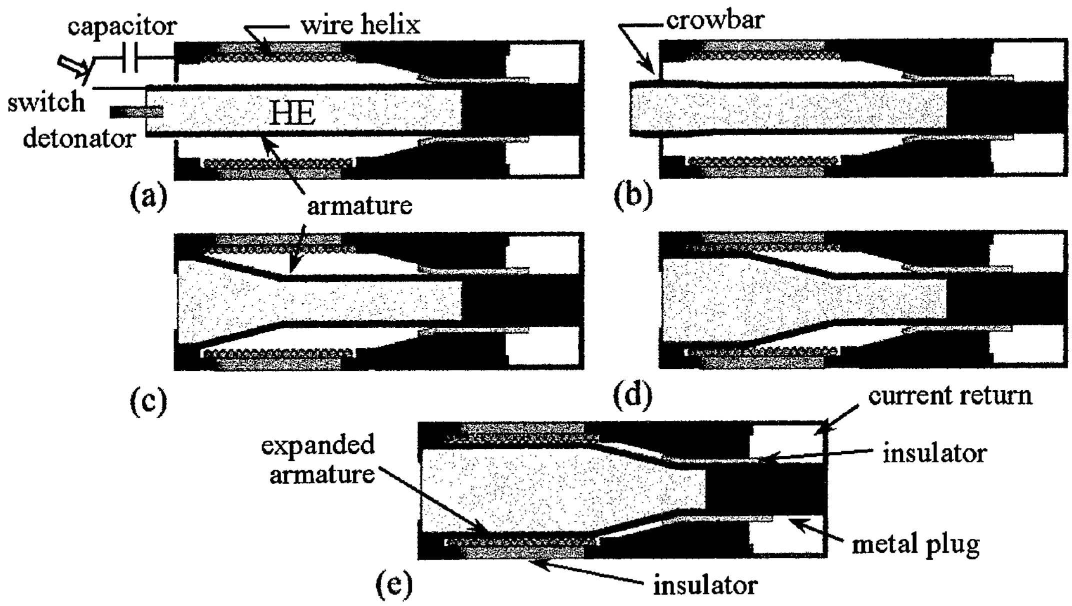

Figure 1 Stages of operation: a) establish seed current, initiate detonation, b) crowbar closure, seed source disconnected, c) contact of armature (metal pipe filled with HE) with first helix turn, d) processing contact between armature and helix, e) final stage.

The first stage of operation for a simple, single-stage helical FCG is the application of a seed current to the generator, which is done, for instance, by closing a switch connecting the generator to a small capacitor bank, see Fig. 1a. After a few 10s of microseconds, the current in the helix will reach a current maximum (LC resonant circuit, with L being the initial inductance of the generator, L_i). The detonator is fired just prior to this current (or magnetic flux) maximum during the seed phase, so that the moment of crowbar, Fig. 1b, coincides approximately with this maximum. To achieve crowbar, the armature will expand radically due to the explosive pressure exerted by the detonation of the HE. This armature expansion will continue throughout the final stages of operation, Figs. 1d and e.

Independent of the physical shape of the flux compression generator, we can estimate the performance of an ideal (loss less) flux compression generator by simply equating the initial and final flux, Φ, in the system.

$$\Phi_i = \Phi_f, \tag{1}$$

or in terms of the generator's initial and final inductance, L, and current, I,

$$L_i \cdot I_i = L_f \cdot I_f \text{ or } I_f = I_i \cdot \frac{L_i}{L_f}. \tag{2}$$

We can further define the current gain, G_I, of a generator by the ratio of initial to final inductance. Theoretically, the larger the initial inductance, L_i, and the smaller the final (load) inductance, L_f, the more gain is expected. Of course, our assumption of ideal flux conservation cannot hold true for a real system, as we will always have ohmic losses in

the conductors and other intrinsic flux losses. However, by adding a figure of merit, β, to equation (2) we can write:

$$G_I = \frac{I_f}{I_i} = \left(\frac{L_i}{L_f}\right)^{\beta} \tag{3}$$

The ideal generator without losses has $\beta = 1$, however, from experiments, we have $\beta \sim 0.6 \ldots 0.8$, for helical flux compression generators, depending on the specific generator design.

A similar expression can be found for the energy gain, G_E, with

$$G_E = \left(\frac{L_i}{L_f}\right)^{2\cdot\beta-1}. \tag{4}$$

It should be noted that for $\beta = 0.5$, no energy will be gained, cf. eq. 4, whereas the current gain, eq. 3, will still be larger than unity. In general, for maximum energy and current gain, one should aim to have a large L_i and a small L_f, while maintaining a value of β as close to 1 as physically possible. Limits are imposed due to the finite conductivity of the conductors always causing ohmic losses and the intrinsic flux loss. The latter is based on the simple fact that not all magnetic flux is compressed but some flux that has diffused into the conductors is not recovered during compression.

B. Generator Losses

The angle of expansion of the armature, the Gurney angle, is determined by the type of HE used and the density as well as dimensions of the metal tube. For C-4 and an aluminum tube with 38 mm O.D. and 2.5 mm wall thickness, the Gurney angle (half angle of the cone) is approximately 15 degrees. Or, in terms of velocities, the detonation velocity of C-4 is ~ 8 km/s and the radial expansion of the armature ~ 2 km/s. The additional mass of the helix (also called stator) and support structure will slow down the armature expansion at the contact, virtually stopping further armature expansion on the microsecond timescale, cf. Figs. 1d and e. However, on a millisecond timescale, the armature, helix, support structure will continue to expand so that typically only small fragments of the generator are recovered postmortem. A fragmentation of the armature prior to contact needs to be avoided at all cost since even fragmentation precursors such as small cracks or ripples will drive up the ohmic resistance of the armature causing additional flux losses. Since the current in the armature mirrors, to a large extent the current flowing in the helix, longitudinal and azimuthal cracks are equally detrimental to generator performance.

Besides the ohmic and intrinsic losses in the FCG (these two losses cannot be avoided), further mechanical imperfections in the generator construction can cause a dramatic fall in performance. Foremost, the armature and stator should be round and centered within a certain tolerance to avoid skipping from turn to turn or partial turns. Knowing the expansion angle, θ, and the wire pitch, p, the tolerance can be estimated by [1] .

$$\Delta a = \frac{p}{4} \tan\theta, \tag{5}$$

For 3 mm pitch, the tolerance, Δa, is ~ 0.2 mm, which is not too difficult to keep. A reasonable lower limit for the wire pitch has been given with ~ 1 mm; below that the generator performance will suffer [2]. In light of this, it is not surprising that the surface finish of the armature has proven to be rather uncritical. No noticeable performance difference was observed when firing FCG's with polished or as-received aluminum armatures. More important is the roundness of the armature and the concentricity between inside and outside diameter of the armature well within the above given tolerance.

If no special measures are taken, the volume between stator and armature will be filled with air, which has moderate mass and moderate electrical breakdown strength. When the induced voltage rises locally above the breakdown strength of the gas, the FCG will again suffer severe losses. In this case, the design has to be reevaluated. For instance, a larger pitch will reduce the induced voltage. Filling the volume with helium has the benefit of lowering the gas dynamic resistance to the armature movement. However, helium has no electronegative component whatsoever, and is thus very prone to electrical breakdown, as has been experimentally verified. Sulfurhexafluoride, SF_6, on the other hand has a very large molecular mass and adds some resistance to the armature expansion. However, its superior insulating properties are so favorable that SF_6 has been used in many FCGs throughout the world. Measurements and FCG simulations [3] indicate that the breakdown strength for air and SF_6 under these extreme conditions is comparable to the value at STP, ~ 30 kV/cm for air and ~ 78 kV/cm for SF_6. The gas is locally trapped between armature and stator and, being highly compressed, basically adds in its final stage somewhat to the dielectric insulation. Both the conventional insulation, e.g. Teflon, and the thin gas layer will eventually break down to allow for armature-stator contact.

C. **Two-stage generator system**

Even at small dimensions of less than 0.5 meter in length end-initiated helical magnetic flux compression generators (FCG) have at least one order of magnitude higher energy density (by weight or volume) than capacitive energy storage with similar discharge time characteristics. However, simple FCGs with a single helix produce high output energy only into low inductance loads, thus producing several 100 kA of current at a voltage level of less than 10 kV. Many pulsed power devices require less current but a considerably higher voltage level. For effectively driving a high inductance load of several μH, a multistage FCG design has been suggested. We successfully tested a dual stage FCG with a total length of 250 mm, a helix inner diameter of 51 mm, which is wound with Teflon insulated stranded wire of different sizes in the range from AWG 12 to AWG 22. We have presently achieved an energy gain of ~ 13.

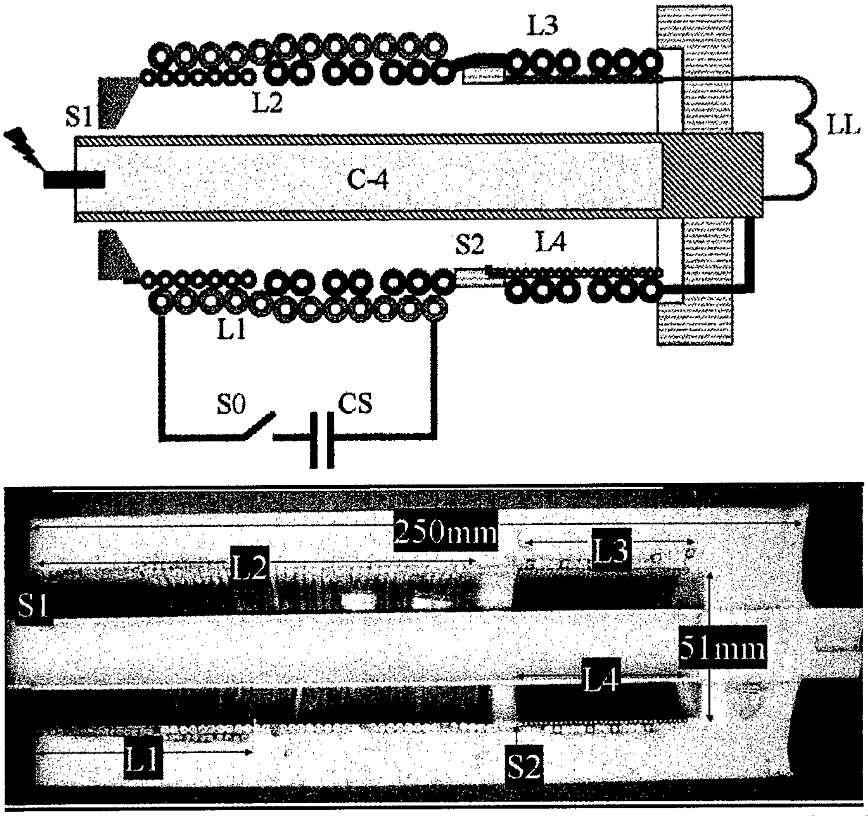

Figure 2: Staged FCG connected to an inductive load, LL. Storage capacitor (50 μF) – CS, Closing switch – S0, field coil for first stage – L1, Crowbar for L2 – S1, first stage coil – L2, primary of dynamic transformer – L3, Crowbar for L4 – S2, secondary of dynamic transformer – L4.

Adding a power conditioning stage (fuse opening switch) to the depicted generator enabled us generating more than 100 kV into a 12 Ohm load. We expect to be able to drive the system of this size as high as 400 kV in the near future.

D. CONCLUSION

Magnetic Flux Compression Generators are a unique source of electromagnetic energy. Their energy per volume or weight is approximately a factor 10 higher than the specific energy of high voltage capacitors. The helical FCG has found the most widespread use in pulsed power applications due to its capability to drive rather large inductive loads. We have emphasized that the scaling of performance with FCG size is such that very small generators (< 50 mm diameter) become very inefficient, allowing only an energy gain of ~ 10 or less if the size is further reduced. On the opposite side of the spectrum, generators with large diameters (10 cm… 1m) work very well, if the design is such that turnskipping and internal breakdown, mostly due to mechanical flaws, are avoided. Besides the FCG, a seed source and a power conditioning stage has to be added and designed to complete an explosive driven pulsed power system. The truly single shot nature of such an explosive

system limits its range of applications. However, the fact that its output power is immediately available whenever needed without relying on much prime energy, its long shelf live, superior energy density, and the comparatively inexpensive construction continue making the explosive driven pulsed power systems attractive.

D. Mini-Dictionary

Armature	Hollow seamless metal tube (aluminum or copper) filled with HE
Crowbar	Two metallic conductors separated by a gap, which will be closed due to explosive deformation (crowbar closure)
FCG	Flux Compression Generator
Gurney angle	The armature's angle of expansion upon detonation of the HE
HE	High explosives
Helix	Copper wire wound to form a spiral.
Loss, avoidable	Losses based on flaws in design or manufacturing. E.g.: Electric breakdown, premature armature breakup, out-of-round armature or helix.
Loss, intrinsic	Magnetic flux that is left behind in the conductors and lost for further compression.
Loss, ohmic	Heating of conductors due to current flow in conductors with finite conductivity (drastically limits the performance of small, inch-sized, generators).
Magnetic flux	Product of current and inductance (conserved in an ideal generator). The flux is trapped between armature and helix during the compression phase.
Stator	see "Helix"
Turnskipping	Describes the armature jumping from helix turn to helix turn without making contact with the helix wire in between. Leads to excessive flux loss and can be avoided in a good design. Also called "clocking"

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2. V. Ye. Fortov, Edtr., Explosive Generators, p. 269-272, Moscow Nauka, 2002 (In Russian).
3. A. Neuber, T. Holt, J. Dickens, and M. Kristiansen, "Thermodynamic State Of The Magnetic Flux Compression Generator Volume," IEEE Trans. on Plasma Science, vol. 30, 1659-1664 (2002), and ref. 5 therein.

HELICAL EXPLOSIVE FLUX COMPRESSION GENERATORS

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The main focus of this research conducted at the Center for Pulsed Power and Power Electronics in the Electrical Engineering department at TTU has been on understanding and characterization of the physics of operation of helical magnetic flux compression generators (HMFCG) and their components. Further, a more applied approach to designing a practical HMFCG was chosen toward the final year of the 5 year program.

To meet the above goals, the following research efforts were completed during the course of this project:

Characterization of Armature Expansion and Generator Operation

High-speed optical diagnostics have been extensively used to study the MFCG operation in detail. Limits of armature expansion, armature-stator interaction have been determined. The detailed results are published in:
"A. Neuber, J. Dickens, H. Krompholz, and M. Kristiansen: Optical Diagnostics on Helical Flux Compression Generators. IEEE Trans. on Plasma Science, vol. 28, 1445-1450 (2000)."

Experimental MFCG Performance Compared to Computer Codes

The measured electrical behavior of simple single-stage MFCG's has been compared with several available computer codes. This revealed that all of the codes available to the researchers at the time failed in a-priori prediction of the MFCG performance. All computer codes had to adjust at least one parameter to match the experimental behavior.
The detailed results are published in:
"A. Neuber, J. Dickens, J. B. Cornette, K. Jamison, R. Parkinson, M. Giesselmann, P. Worsey, J. Baird, M. Schmidt, and M. Kristiansen, "Electrical Behavior of a Simple Helical Flux Compression Generator for Code Benchmarking," IEEE Trans. on Plasma Science, vol. 29, 573-581 (2001)."

Explosive Test Facility Installed at TTU

The initial MFCG tests were carried out by researchers from TTU and UMR at UMR. However, most equipment had to be shipped from TTU to UMR, such as high power laser, fast oscilloscopes, high-speed cameras, etc. This added shipping cost to the project as well as repair cost for equipment damaged during shipment. After approx. one year into the program, TTU had established an explosives facility and the personnel were trained in handling HE. At present, the Center for Pulsed Power and Power Electronics at TTU is, to our knowledge, the only university laboratory in the US that has the combined expertise of Electrical and Explosive Engineering.

Characterization of Temperature and Pressure of the Shocked and Electrically Stressed Gas Inside an HMFCG

The transient change of gas/plasma on the inside of the HMFCG can cause generator failure due to electrical breakdown. The breakdown strength of gases such as SF_6, air, and argon has been measured in-situ during generator operation.
The detailed results are published in:
"A. Neuber, T. Holt, J. Dickens, and M. Kristiansen, "Thermodynamic State Of The Magnetic Flux Compression Generator Volume," IEEE Trans. on Plasma Science, vol. 30, 1659-1664 (2002)."

Relation between Generator Geometry (Size) and Performance (Scaling Law)

We have shown, based on experimental evidence from our own research and other sources, that small HMFCGs (< 2" in diameter) run into physical limits and are very inefficient or unsuitable for energy multiplication. We have corroborated this experimental evidence by a theoretical analysis of the generator performance based on physics principles. This enabled us for the first time, to truly a-priori predict/estimate the HMFCG performance.

The detailed results are published in:

"A. Neuber, T. Holt, J. Hernandez, J. Dickens, and M. Kristiansen, "Geometry Impact on Flux Losses in MFCGs," presented at the Ninth International Conference on Megagauss Magnetic Field Generation and Related Topics, Moscow – St. Petersburg, July 7-14, 2002."
and
"A. Neuber, T. Holt, J. Hernandez, J. Dickens, and M. Kristiansen, "Physical Efficiency Limits Of Inch-Sized Helical MFCG's," Proceedings of the 14^{th} IEEE Pulsed Power Conference, Dallas, TX, June 15-18, 2003."

Comparison between Shocked Ferromagnetic and Ferroelectric Materials as HMFCG Seed Source

We have developed several schemes for generating the needed seed energy by explosively extracting the energy from permanent magnetic or electric materials. Ferroelectric Materials exhibit superior performance (higher energy output per weight).

The detailed results are described in:
"N. Schoeneberg, J. Walter, A. Neuber, J. Dickens, and M. Kristiansen, "Ferromagnetic And Ferroelectric Materials As Seed Sources For Magnetic Flux Compressors," Proceedings of the 14th IEEE Pulsed Power Conference, Dallas, TX, June 15-18, 2003."

More Applied HMFCG Design and Tests

Based on our prior single-stage HMFCGs for basic physics studies, we developed a 2-stage MFCG with varying pitch. This generator can drive a high inductance load, as it is required for high voltage pulse power generation (A single-stage generator only runs efficiently into very low inductance loads). Such a generator can be used as driver for high power microwave sources.

The detailed results are published in: "Andreas A. Neuber, Juan-Carlos Hernández, James C. Dickens, Magne Kristiansen, "Helical MFCG For Driving A High Inductance Load," accepted for publication in the Special Edition of the Journal of EM Phenomenon on FCGs (Oct. 2003)."

ELECTRICAL AND MECHANICAL MATERIALS PROPERTIES

Jahan Rasty, Associate Professor
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Lubbock, TX

The general focus of the research conducted at the Mechanical Engineering Department at TTU has been on understanding and characterization of the mechanical and electrical properties of the armature and stator material under conditions of shock and high strain-rate loading.

To meet the above goals, the following research efforts were completed during the course of this project:

Design and Construction of a Split Hopkinson Pressure Bar (SHPB) for High Strain-Rate Testing of Material Behavior

This apparatus was designed for subjecting materials to compressive shock waves at high strain rates. The apparatus was used to measure the effect of shock loading on the electrical properties of typical armature materials such as aluminum and copper. Furthermore, the apparatus was utilized to determine the stress-strain behavior of copper and aluminum armature materials for input into the finite element simulation models.

The use of the SHPB apparatus proved to be successful due to its ability to produce a uniform shock load and its ease of control. In most previous research in this area, an explosive driven impactor has usually been used to simulate the necessary shock loading. However, difficulties associated with controlling the magnitude of the shock pressure have made the repeatability of the results quite challenging. A SHPB apparatus proved to be quite useful for subjecting OFHC copper specimens to various shock pressures.

Hydrodynamic Finite Element Simulation of Armature Expansion

A hydrodynamic Finite Element (FE) model was developed to simulate the expansion characteristics of the armature and its ensuing impact with the stator. The effectiveness of the FE model to simulate the explosive behavior of the armature was qualified by comparing the numerical results with experimentally measured parameters. The following topics were investigated utilizing the FE model:

Expansion angle and expansion shape (profile) of aluminum and copper armatures,
Quantification of the severity of the "end effect" of an expanding armature,
Effect of wall thickness-to-radius ratio on the expansion behavior,
Determination of the axial velocity of the contact point at the armature/stator interface,
Simulation of the expansion behavior in the template generator built at TTU-PPPE,

Estimation of the rise in air temperature between the armature and the stator during the expansion process,

Estimation of the rise in temperature of the armature material during the expansion process,

Simulation of the armature fragmentation during the expansion process.

Summary of findings from FE Simulations:

- The radial displacement of the armature as well as the axial velocity of the armature/stator contact point were measured experimentally and compared with numerical results showing excellent agreement between the two.

- The results indicate that the radial and axial velocity with which the armature impacts the stator does not change throughout the length of the armature.

- The results show that the velocity with which the contact point between the armature and the stator travels along the length of the armature, decreased with increasing post detonation time.

- As expected, the axial propagation velocity of the contact point was found to be at its highest value (2.25 times detonation velocity) at the region close to the detonation end, while approaching the detonation velocity at points away from the detonation end.

- There is considerable "jetting" of the insulation and armature material as the armature impacts the stator's insulation material.

- The stator wire's insulation material begins a rapid fragmentation and separation from the stator wire upon armature's impact. However, due to the severe "jetting" of the armature material through the spacing between consecutive turns of the helical stator, some of the fragmented insulation material is trapped between the armature and the solid copper stator wire. The rest of the insulation material on the other side of the armature/stator interface is jetted out of the armature/stator impact zone.

- The solid copper component of the stator wire shows a significant amount of plastic deformation when impacted by the armature. However, the radial displacement of the stator wire is minimal while there is a significant amount of jetting of armature material through the spacing between the stator wires.

- During the impact phase of the armature with the helical wire core/insulation, the insulation material is forced to move along the surface of its surrounding wire core. Most of the insulation material is shortly squeezed out of the contact zone. However, some of the fragmented insulation material remains trapped between the armature and the wire core.

- The insulation/wire core behavior at different turns of the helical turn is not totally identical because the exact location of the fragmentation point of the insulation layer is different from one turn to the next.

- The breakdown time of the insulation at each turn, which is the time required for the armature to fragment the insulation resulting in contact with the wire core, has a small variation from one turn to the next with an average value of 0.45 μs.

- There is a small axial shift (axial displacement) of the helical turns. However, the maximum axial displacement of the wire core at the contact point with the armature is just 13 percent of the thickness of the wire insulation for the template generator considered in this research. Therefore, the deformed wire core does not break through the adjacent insulation to contact the adjacent wire core.

Electrical Conductivity of Oxygen-Free High-Conductivity Copper Under Conditions of Shock and High Strain-Rate Loading

The main purpose of this study was to measure the electrical conductivity of OFHC copper and to characterize the effect of varying shock pressures, as well as the material's heat treatment, on the ensuing changes in the electrical conductivity of the material. In most previous research in this area, an explosive driven impactor has usually been used to simulate the necessary shock loading. However, difficulties associated with controlling the magnitude of the shock pressure, have made the repeatability of the results quite challenging. A Split Hopkinson Pressure Bar apparatus proved to be quite useful for subjecting OFHC copper specimens to various shock pressures, due to its ability to produce a uniform and repeatable shock load, and ease of control. Measurements of the specimen's resistivity indicated that exposure to shock loading results in the material's resistivity to decrease initially, followed by a sharp increase in its resistivity, before decreasing to a steady state value. Depending on the magnitude of the shock pressure, resistivity changes in excess of 200% were recorded. Comparison of the results for the as-received and annealed copper specimens indicates that shock-induced resistivity of copper increases to a greater extent in the as-received material than that of the annealed material at the same shock pressure.

The SHPB apparatus was capable of producing strain rates up to the fracture limit of the samples tested. Actual fracturing of samples would not have allowed detailed analysis of the thermal and mechanical effects on the sample resistivity changes. Sample strain rate levels of up to 10^4 sec^{-1} were achieved with the apparatus on OFHC copper and aluminum samples. This may be comparable to switching contacts under similar shock-loading and is an order of magnitude less than the expected strain rates in the MFCG. Sample resistivity showed an initial and abrupt decrease followed by a rapid increase during loading to levels twice that of virgin samples. Short and long time based resistivity

monitoring and high speed framing photography allowed differentiation between changes in resistivity due to bulk material deformation, and changes due to thermal effects.

As stated before, the experimental results indicate that the resistivity of the material initially decreases upon exposure to the shock wave pressure. At this stage, the particle velocity of the material is much slower than the shock wave velocity, therefore, the thermal and deformation effects are negligible and the decrease in the material's resistivity can be solely attributed to the pressure build up as a result of the exposure to the shock wave. The decrease in the material's resistivity can be attributed to the reduction of the amplitudes of the lattice vibration as the shock wave pressure is built up in the material. Previous research in this area has shown that the resistivity does not continue to decrease monotonically as the pressure is increased. It has been shown that the resistivity eventually passes through a minimum and increases as the pressure is increased past a transition pressure due to crystallographic phase transitions or changes in the electronic configuration of the metal.

Mechanical Property and Metallurgical Tests

Any pre-existing or induced crack in the armature before its contacts with the stator wire will cause serious magnetic field diffusion and additional magnetic flux loss resulting in decreased performance of the generator. Knowledge of crack formation mechanism and micro-structural evolution of the armature material during its expansion process is necessary for optimum armature design. In this study, aluminum 6061-T6 armatures were subjected to explosive shock-loading via Comp C-4 high explosive. Explosive experiments were conducted by utilizing a wood-lined detonation chamber in order to catch the armature fragments for subsequent metallurgical observation. Microstructure examinations were conducted on collected fragments, as well as the original material, utilizing a light metallography technique. The research results clearly show that the initiation and propagation of axial cracks is the dominating crack mechanism during the armature expansion process.

Effect of Surface Finish on Armature Expansion Characteristics

A number of copper and aluminum armatures with varying degrees of surface finish were prepared. Some armatures were marked with deep axial gouge marks to investigate the effect of extreme surface finish. In addition, some armatures were prepared with four internal and/or external axial grooves, 90 degrees apart, to see if any improvements in expansion characteristics of the armatures can be observed. The results showed that surface finish does not play a significant role on the expansion characteristics of the armature.

Effect of Scaling on Armature Expansion

We explored the effect of "scaling" on the armature's expansion angle using a series of numerical parametric experiments. Our research showed that:

- The armature expansion angle is independent of the "scaling" factor. The expansion angle of the armature is determined by the physical properties (density) of the armature's material, explosive properties (density), and the wall-thickness-to-radius ratio of the armature.

- The expansion angle of the armature in an MFCG, as calculated from the Gurney equation, is much larger than the actual expansion angle of the armature, as observed experimental or simulated numerically. This discrepancy can be attributed to the Gurney equation assumption that the explosive products in an MFCG are completely confined.

- In a typical MFCG, the explosive products (gases) are not completely confined due to either the open-end configuration of the armature or the natural fragmentation of the armature during the explosion process. A "modified Gurney equation" was developed, which provides a more accurate estimate (relative error within 10%) of the expansion angle for armatures used in this research, namely, aluminum or copper armatures charged with C-4 high explosive.

Calculation of Air Temperature and Pressure History During the Operation of MFCGs

During the operation of MFCGs, the gas-plasma, shocked by the rapidly expanding armature, could lead to electrical arcing across the gas between the armature and the stator at locations where physical contact between the armature and stator has not yet occurred. This will result in a loss of magnetic flux and a decrease in the electrical efficiency of the MFCG. Therefore, knowledge of the ensuing gas temperature and pressure histories is necessary for identification of loss mechanisms in an effort to optimize the efficiency of MFCGs. In this part of our research, we focused on estimating the air temperature and pressure histories via Finite Element (FE) simulation of the armature expansion and its ensuing contact with the stator in an MFCG. First, the validity of the FE model was verified by comparing deformation contours obtained from the simulations to those obtained experimentally via high-speed photography. Utilizing the pressure history data obtained from the FE results, the air temperature was calculated theoretically. The results indicate that the air pressure and temperature in an MFCG, having a compression ratio of 1.8, could be as high as 30 MPa and 4000° K, respectively.

Multilayer Armatures

We experimented with multi-layer (up to tri-layer) armature construction to investigate the effect of various materials, and their combination, on the expansion characteristics of the armature. Armatures of similar thickness, outer radius, and inner radius were constructed of 100% Al, 75% Al - 25% Cu, 50% Al - 50% Cu, 25% Al - 75% Cu, and 100% Cu. In addition similar size tri-layer armatures were made having a 33% inner Al layer, 33% polymer mid-layer, and a 33% Cu outer layer. High-speed photography was used to document the expansion behavior of above armatures under a full charge of C-4. The results indicate that:

- When the expansion behavior of the armature is of primary concern, aluminum 6061-T6 armature is the best among five possible armatures studied in this study.

- When the outer layer of the armature is required or preferred to be of OFHC copper material for achieving high conductivity, the tri-layer armature consisting of copper outer layer, aluminum inner layer separated by a polymer intermediate layer, shows the best expansion behavior.

Design Criteria

One of the main sources of magnetic flux loss is the "turn-skipping" phenomenon, in which the expanding armature fails to establish contact with every turn of the helical coil, resulting in magnetic flux loss in the skipped turns of the coil. In this part of our research, design criteria for prevention of "turn-skipping" are presented in order to achieve optimum MFCG performance. The "turn-skipping" phenomenon was related to non-uniform or asymmetric expansion of the armature, as well as detonation end effects. Equations describing the "turn skipping" phenomenon were developed in terms of the eccentricity of the armature with respect to the helical coil, the armature's wall thickness variations and the length of the detonation "end effect".

POWER CONDITIONING FOR HELICAL FLUX COMPRESSION GENERATORS

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Introduction:

Magnetic Flux Compression Generators (MFCGs) are compact devices with high energy density and power output capability. MFCGs typically have output currents of hundreds of kilo amps up to mega-amps and voltages in the range of several kV. The voltage and current parameters as well as the time-scale of the power output of an MFCG are not suitable to drive high power microwave loads directly. Microwave loads typically need voltages of 500 kV and currents of several tens of kA for about a μs. Therefore, it is necessary to include a power conditioning and pulse compression system between the output of the MFCG and the load. In addition, some microwave sources either benefit from or require a constant output voltage. To obtain constant output voltages, we investigated pulse shaping with high power Metal Oxide Varistors, (MOVs). The main power conditioning system we chose uses inductive energy storage and an opening switch, which consists of an exploding wire fuse. This scheme achieves voltage and current transformation as well as pulse compression at the same time. The system is suitable for use with a magnetic flux compression generator (MFCG) since the MFCG delivers high current into a small storage inductor.

Summary:

During the project the following achievements have been made:

- We designed and build an experimental laboratory setup to study power conditioning with very detailed diagnostics.
- We investigated the performance of exploding wire fuses as a function of fuse material, fuse mass, and number of fuse wires.
- We created a large data-base with very extensive documentation and sophisticated post-processing.
- We investigated the use of MOV's for pulse shaping.
- The heat-up phase of the fuse has been studied using a thermal imaging camera.
- The explosion phase of the fuse has been studied using an Imacon multi-frame high-speed imaging camera.
- We performed extensive theoretical investigation on the fuse opening process (Ph.D. dissertation).
- We designed and build a fieldable, compact version of the exploding wire fuse that permits integration with magnetic flux compression generators.
- We investigated power conditioning using tightly coupled iron-core transformers.

- We created a comprehensive model for the exploding wire fuse for use in circuit simulators for prediction of system performance.
- We wrote several chapters in the forthcoming comprehensive Handbook on Helical Magnetic Flux Compression Generators.

Initial Experimental Setup:

Figure 1 shows a drawing of the initial experimental setup. The system consists of a primary storage capacitor (Maxwell 52 μF, 40 kV peak voltage), a triggered spark gap used as a closing switch, the energy storage inductor, the exploding wire fuse, the MOV stack, a peaking gap, and a 13 Ω load resistor. In order to observe the heating phase of the fuse, the peaking gap was closed. The peaking gap will be necessary, if a microwave diode is used in place of the resistive load. The fuse section and the enclosure of the peaking gap were filled with SF_6 mixed with nitrogen at an approximate 1/1 ratio. The active length of the fuse was 48 cm. The coaxial enclosure of the load resistor was filled with transformer oil. The fuse was constructed of filaments of thin metal wires. In order to aid in the suppression of the arc after the explosion of the fuse, the fuse wires were embedded in fine sand used for sandblasting, identified as 2W580, made by Potters Industries. Figure 2 shows typical results obtained from this system.

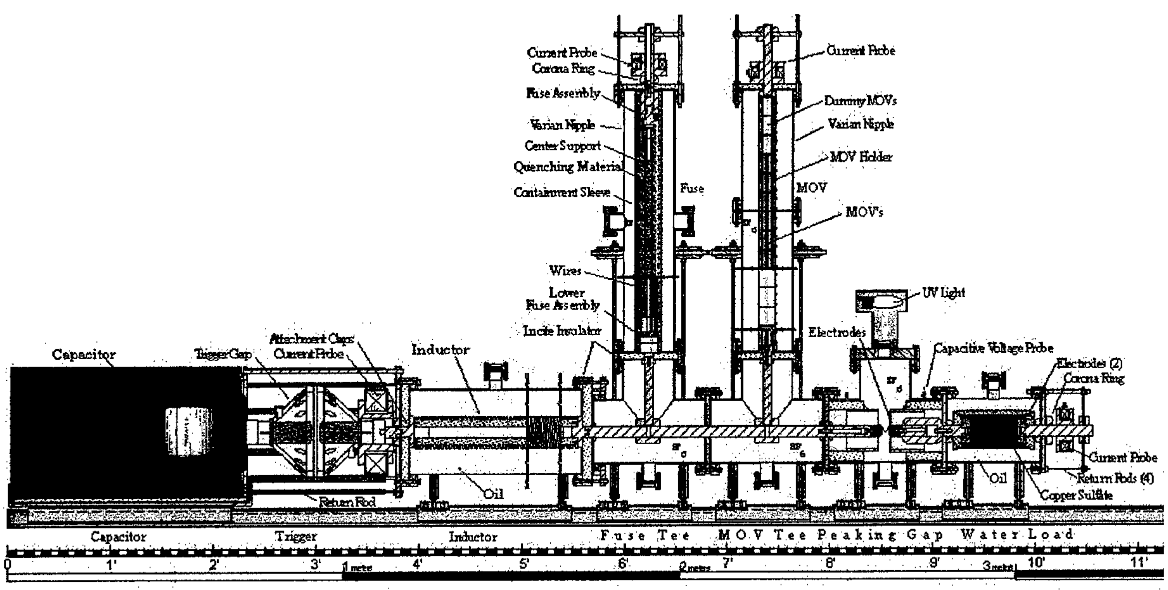

Figure 1: Initial Experimental Setup for Power Conditioning Research

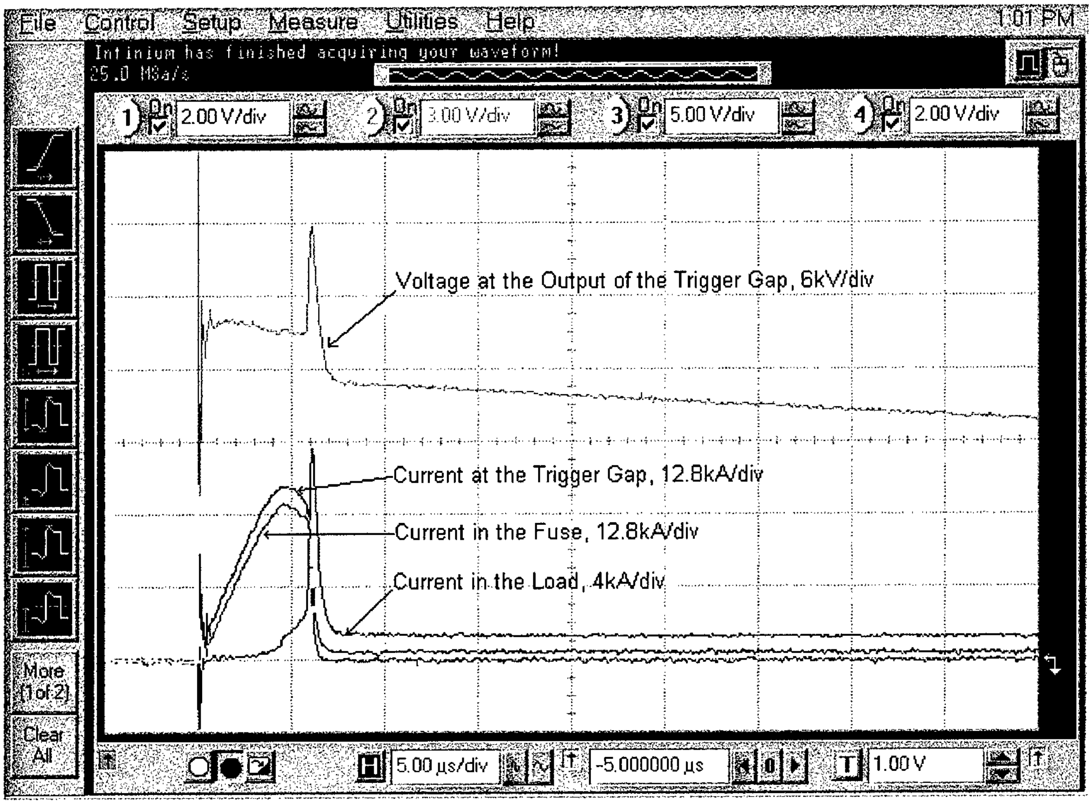

Figure 2: Typical results from Power Conditioning System.

Influence of the Fuse Material:

In order to determine the influence of the fuse material on the performance of the power conditioning system, we tried fuses made out of copper (Cu), silver (Ag), and aluminum (Al). We used comparable numbers of wires, wire diameters and total wire cross sections for all three cases. We observed that the material choice has a significant influence on the fuse performance such that silver fuses exhibit the best performance, followed by copper and, as a distant third, aluminum.

The process of current-interruption by the fuse is the most critical performance parameter of the system. Ideally, the fuse should open at the instant of the current peak in the inductor, L_o, which had a value of 3.5 μH, absorb no energy and instantaneously commutate the current from the inductor into the load. Fuse performance is, therefore, measurable by calculating the derivative of the fuse current and by relating the energy deposit in the fuse to the energy deposited into the load.

Figure 3 shows typical waveforms for silver, copper, and aluminum fuse wires. The superiority of silver as a fuse material is obvious.

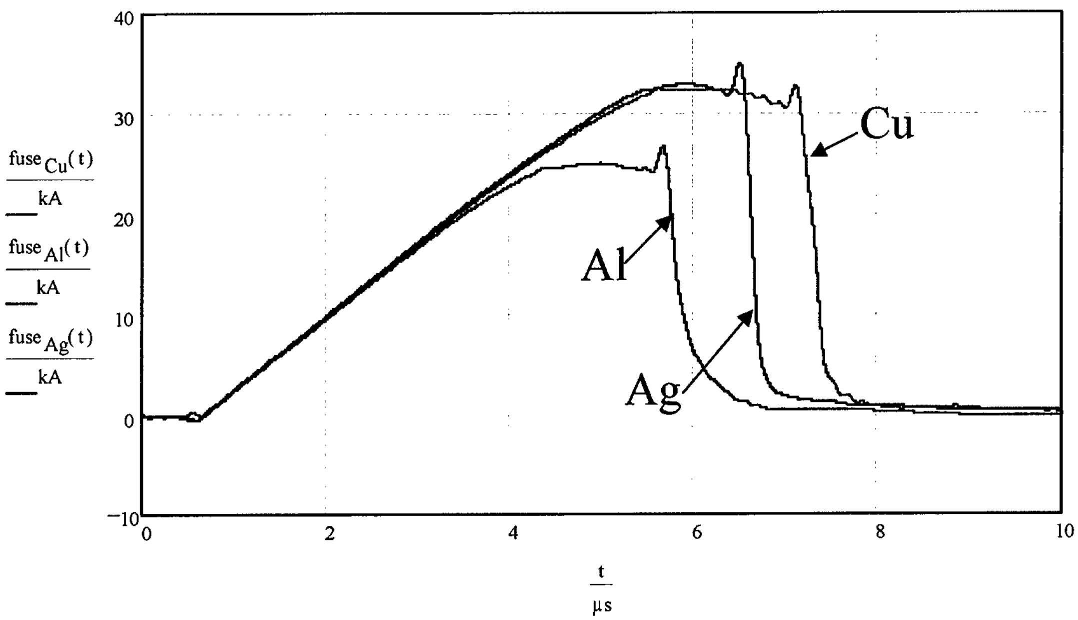

Figure 3: Typical Fuse Currents for Silver, Copper, and Aluminum Fuses.

Optical High Speed Diagnostics:
In order to study the late heat-up and explosion phase of the fuse in greater detail, we took high-speed photographs of the fuse wires during the plasma formation phase. For this purpose, we replaced the stainless steel current return tube of the fuse section with a transparent tube. A picture of the fuse with the transparent tube is shown in Figure 4.

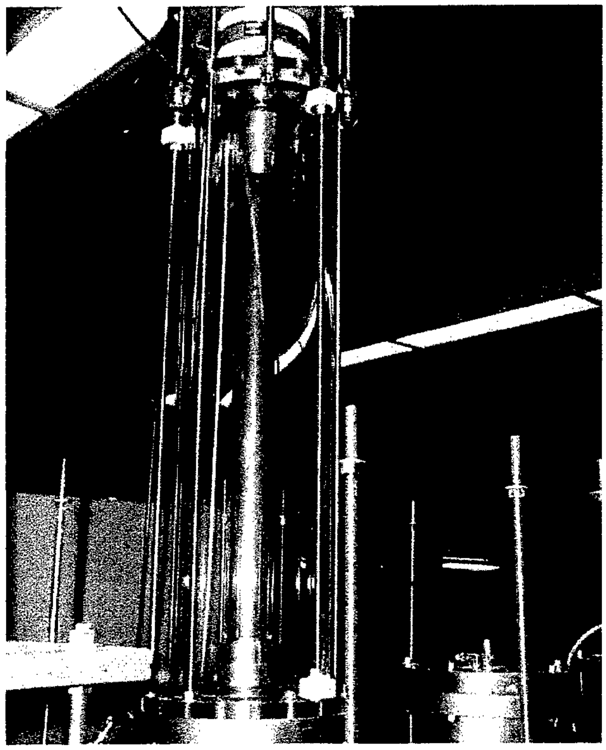

Figure 4: Fuse Assembly with Transparent Tube for Optical Diagnostics.

Data Acquisition System for Optical High Speed Diagnostics:

To study the fuse opening process in detail, we took photographs of the exploding fuse filaments using an IMACON high-speed framing camera. The camera is capable of both framing and streak modes of operation. For our investigations, the camera was operated in multi-frame mode.

We outfitted the IMACON camera with a high resolution CCD camera that captures the data. The CCD sensor is proximity focused, i.e. it is carefully mounted to fit flush onto the phosphor output window of the IMACON camera. When the IMACON camera is triggered, a burst of electrons is send to the phosphor output window, which makes the phosphor glow at the places where it is being hit. The time delay between the excitation of parts of the phosphor is so small compared to the read-out timing of the CCD camera, that the CCD image represents a complete spatial image of the phosphor excitation. Figure 5 shows the entire experimental setup for the high-speed diagnostics. Figure 6 shows some typical results showing MHD type instabilities that develop during the fuse vaporization process.

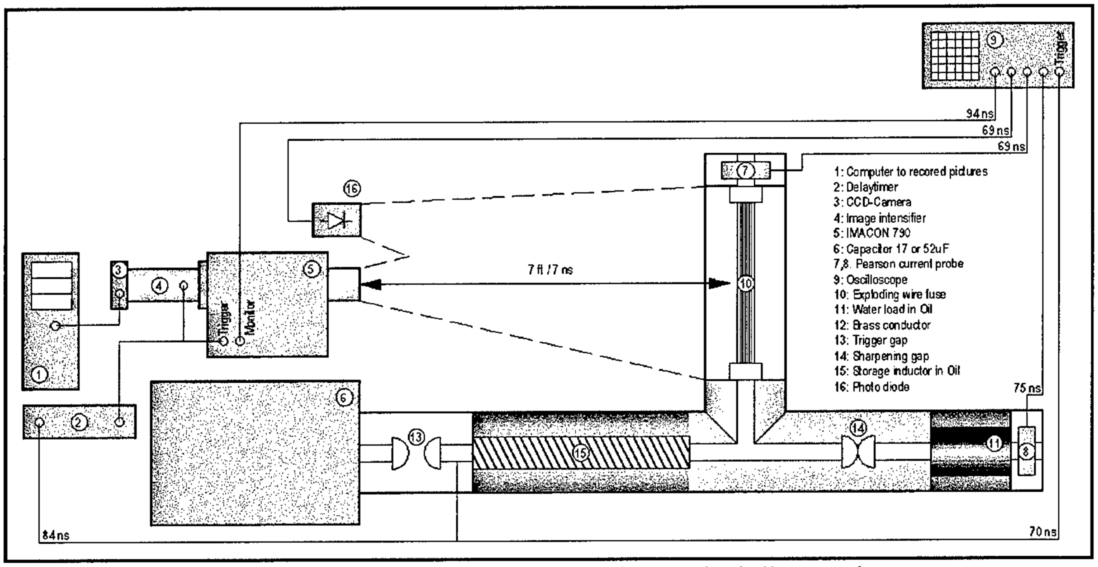

Figure 5: Experimental setup for High Speed Framing optical diagnostics.

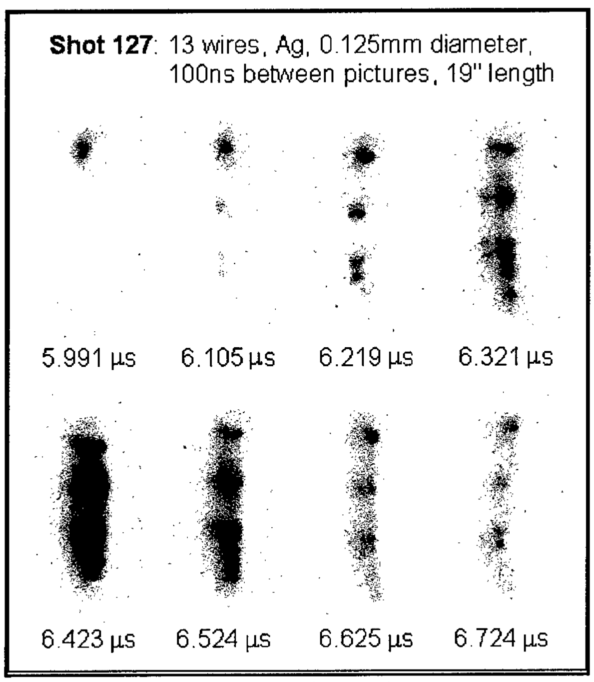

Figure 6: Set of pictures showing the full fuse with 100 ns plug-in for shot 127, 48 cm object height

Improved Power Conditioning System (PCS)

The old PCS shown in Figure 1 was designed to provide maximum flexibility and adaptability. It provided easy access to the fuse section, various ports for a sharpening gap and an additional "T-section" for pulse shaping using MOVs (Metal Oxide Varistor). In addition a number of gas inlets for different sections of the PCS where available. However, this design imposed a number of difficulties to the system.

The insulating material in the inductor section was transformer oil. This does not only make the system very heavy it also makes it impossible to change the inductor in a timely fashion. Furthermore, it creates major problems and extensive destruction if an accidental discharge occurs within the oil.

The free-standing fuse with its T-section degrades the performance of the system since the additional parasitic inductance traps energy that is lost after explosion of the wires. We showed that this accounts for about 25 kV of load voltage. Also, by going away from a pure coaxial design the current distribution in the fuse itself is uneven, which causes the wires to explode at slightly different times.

The physical size and cost of the system makes it impossible to be tested in conjunction with a Magnetic Flux Compression Generator (MFCG). It is too large to be included into our explosion chamber and to expensive to be destroyed every single shot. Connecting it with cables would substantially increase the load inductance on the MFCG and dramatically reduce its performance.

The improved In-Line PCS shown in Figure 7 addresses these points in multiple ways. The first iteration incorporates the inductor and fuse in a single cartridge. It eliminates the need for a T-Section and eliminates the energy loss in the parasitic inductance in the fuse section since it is now part of the main inductance. In addition, sand formerly used as the main insulating material in the fuse, now serves also as the insulating material for the inductor and removes the need for oil.

The subsequent step is to take away the sharpening gap and attach the load directly to the inductor/ fuse. This gives us the ability to build a low cost, compact, disposable power conditioning devices that can easily be attached to the MFCG for a combined test of MFCG and PCS. The peaking gap may, however, be needed, if the load is a Vircator instead of a resistive dummy load.

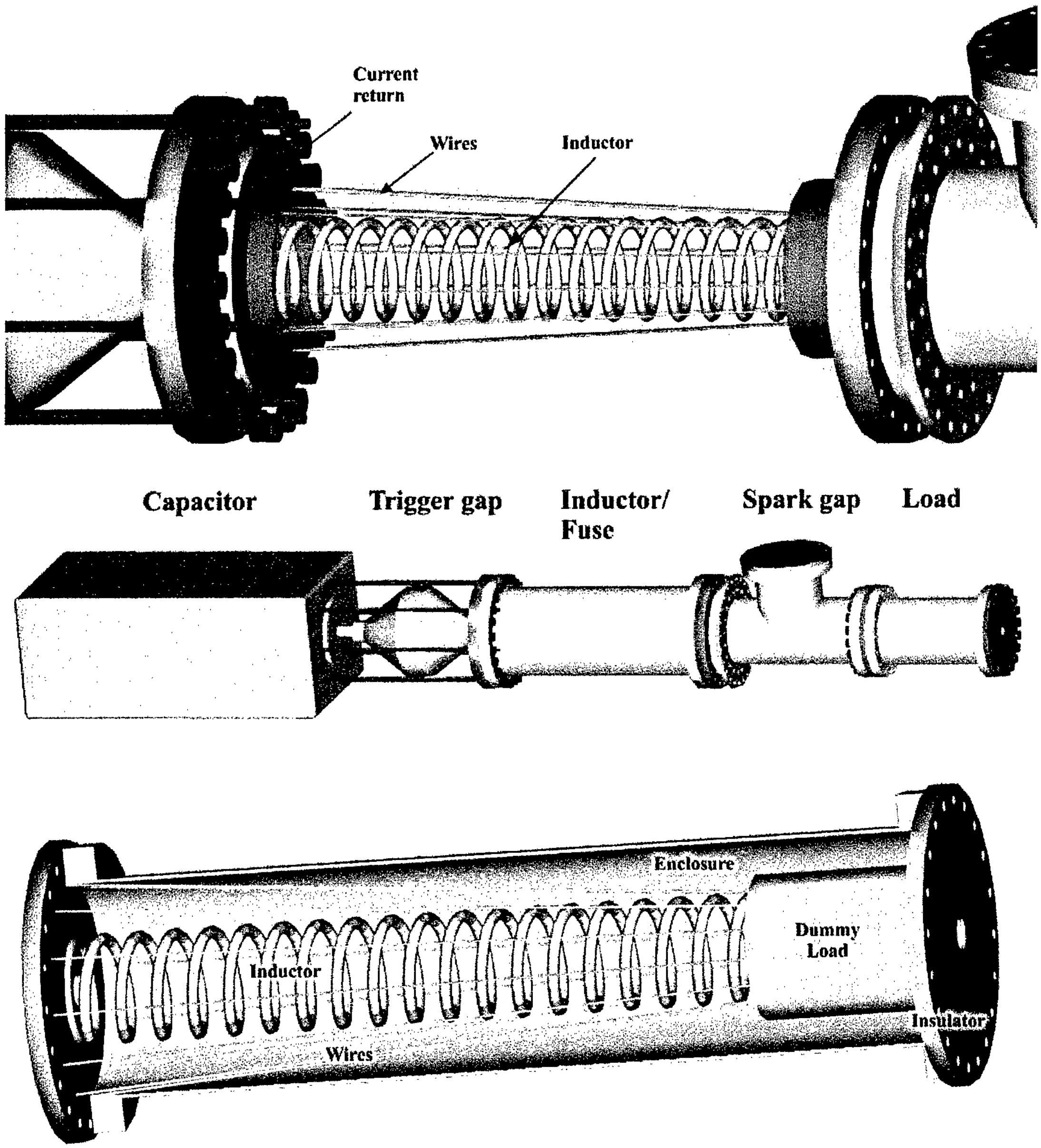

Figure 7: Improved Inductor/Fuse Assembly.

Energy Extraction using Transformers

Instead of directly coupling the energy of the MFCG into the PCS and into the desired load, it can be coupled out with the means of strongly coupled transformers with ferromagnetic cores. A resonant scheme with Air-Core Transformers with approx. 70% coupling is not feasible since a resonant scheme requires a strong match of primary inductance and capacitance as well as secondary inductance and capacitance. Due to the collapsing winding of the MFCG the primary inductance changing constantly, it is impossible to achieve a match. Also, the energy can not be directly coupled into a capacitor and any other high impedance load since the collapsing size of the MFCG cannot handle high voltages.

Figure 8 shows a possible transformer in comparison with the MFCG. The main limiting factor for a single shot extraction of energy is the saturation limit of the transformer. Figure 9 shows the result of a RC discharge though the primary of the transformer. The secondary was connected to a 300 nF capacitor. The voltage on the output capacitor as well as the primary and secondary currents are shown. Using these data, the saturation flux density can easily be calculated. Figure 10 shows a flash x-ray of the transformer. It can be used to determine the physical dimensions of the core, as well as other parameters of it. To yield higher extraction rates, the primary sides of multiple transformers can be connected in series. This would delay the saturation and yield much higher voltages on the output capacitor.

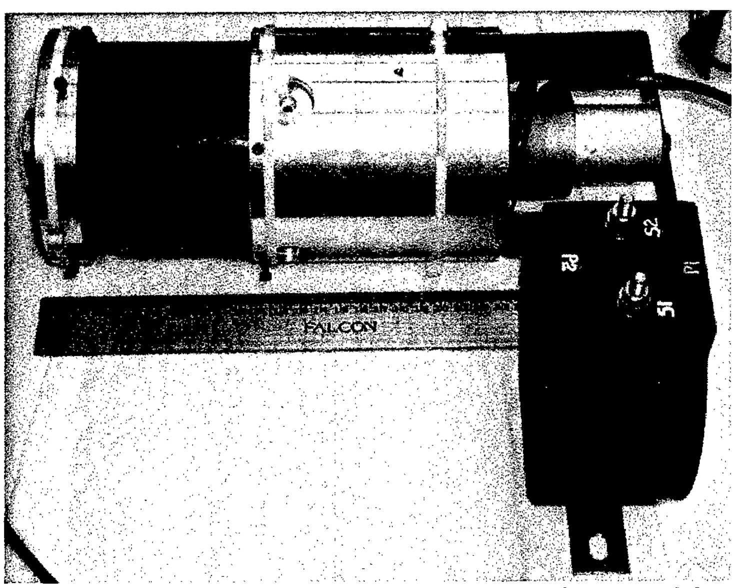

Figure 8: Transformer for energy extraction from MFCG.

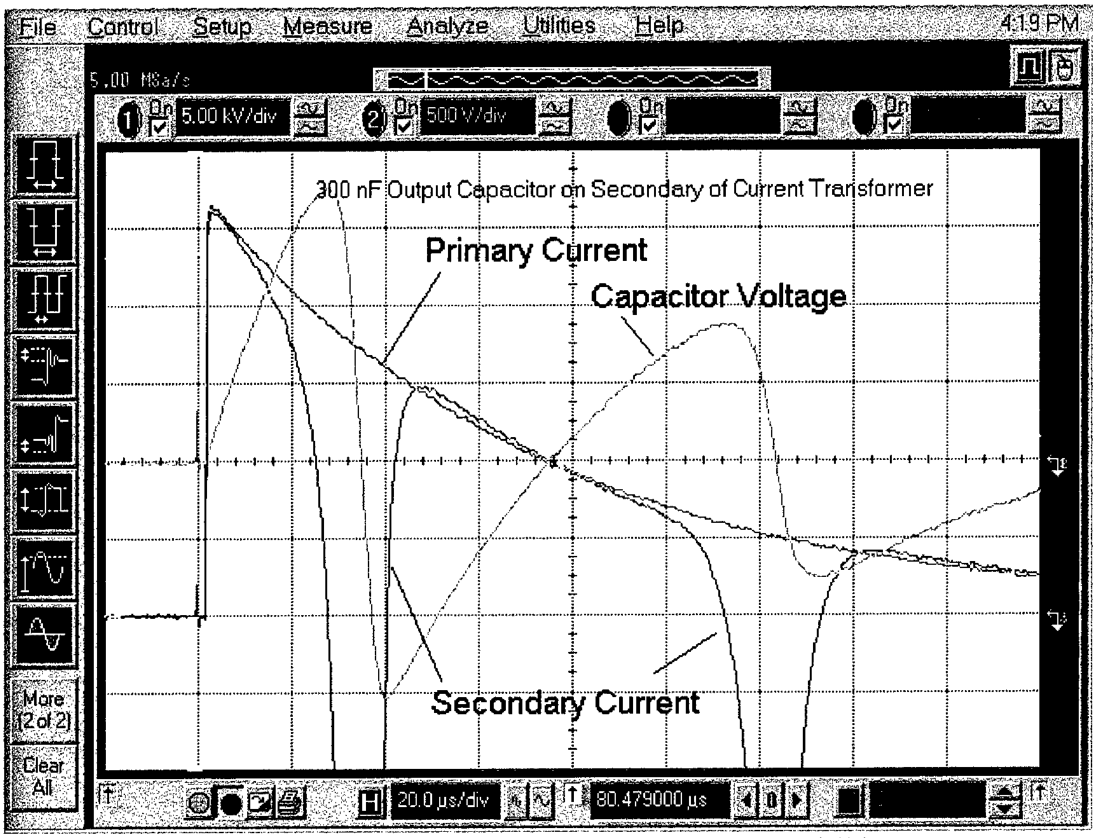

Figure 9: Results with 300nF Capacitor in output loop, saturation visible

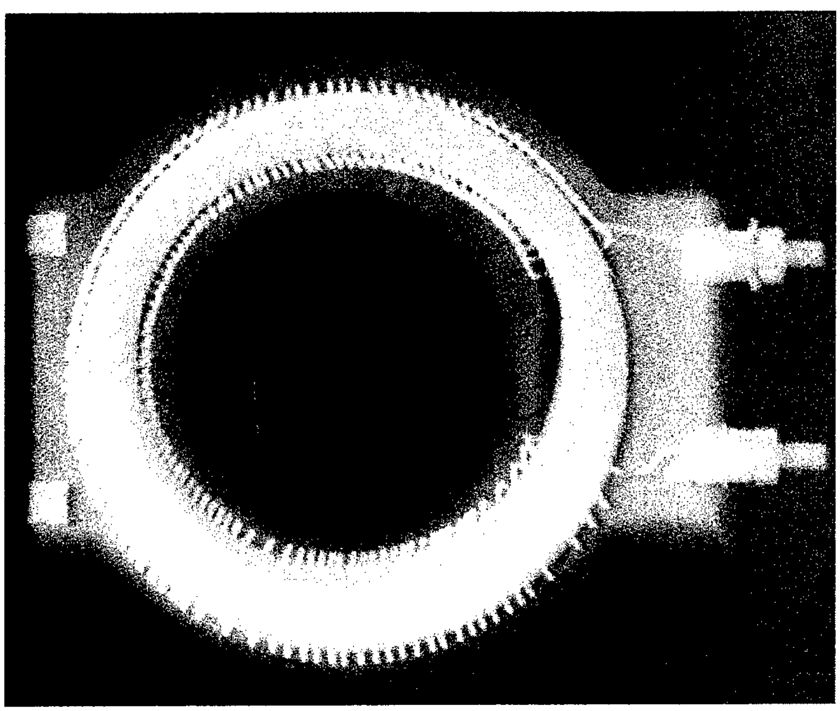

Figure 10: Flash X-ray image of current transformer

Plasma Modeling of Exploding Wire Fuses

We performed the following tasks to model the exploding phase of the fuse wires based on established plasma-physics theory. We also performed an extensive survey of all available literature on this subject.

- Modeled Plasma Parameters of exploding wires using non-ideal State Equation parameters and Shock-Wave Physics
- Achieved ability to plot temperatures and pressures of the plasma as well as the remaining solid core as a function of time and radius (Figure 11)
- Using plasma parameters we obtain first results for the resistance of the plasma channel as a function of time

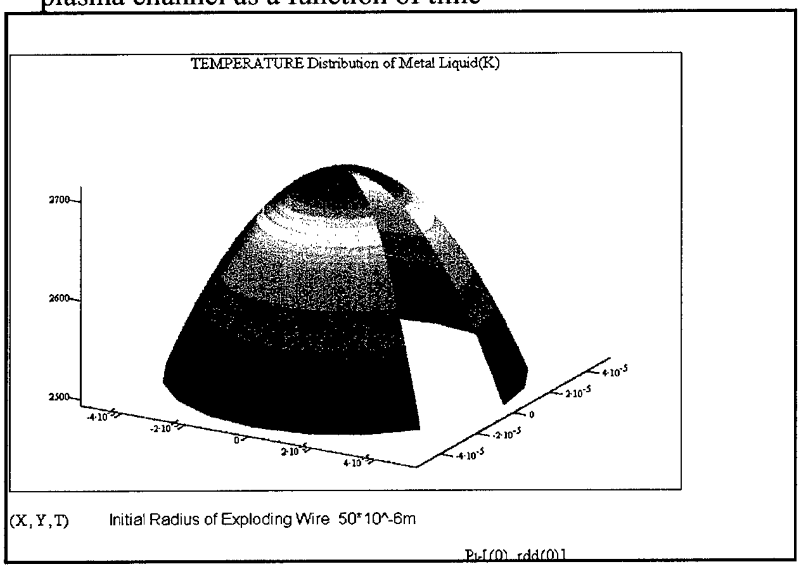

Figure 11: Temperature Profile of Exploding Wire

Comprehensive Performance Modeling of PCS Components:

The exploding wire fuse is the most important component of an inductive energy storage system. The fuse conducts current during the energy buildup phase, and commutates the energy into the load when it opens. The performance of the system is critically dependent on the precise opening characteristics. The explosion of the fuse wires can be broken down into two separate phases. In the first phase, the wires heat up due to energy input until parts of the wires explode. We have shown that not all wires explode simultaneously and plasma instabilities can occur. The explosion of the wires is a very complex process and through exhaustive study of the literature and our experimental results, we generated a set of equations, which describe the dynamic behavior of the fuse as a circuit element very accurately.

$\beta := 25 \qquad \gamma := 190$

Equation 1

$$\rho(t) := \begin{cases} \left[1 + \beta \cdot \left(\dfrac{\int_{0 \cdot \mu s}^{t} J_{Wire}(t)^2 \, dt}{BlowLimit_{Cu}} \right)^{2.5} \right] & \text{if } \int_{0 \cdot \mu s}^{t} J_{Wire}(t)^2 \, dt \le BlowLimit_{Cu} \\ \left[\beta + e^{\left(\dfrac{\int_{0 \cdot \mu s}^{t} J_{Wire}(t)^2 \, dt - BlowLimit_{Cu}}{BlowLimit_{Cu}} \right) \cdot \gamma} \right] & \text{otherwise} \end{cases}$$

Equation 1 shows an expression for the relative resistivity, ρ, as a function of time for the two phases of fuse opening. The relative resistivity, ρ, is a dimensionless number. It has a starting value of unity at t=0. The relative resistivity, ρ, is a multiplier for the fuse resistance, if the combined resistance of the array of fuse wires at room temperature is considered to be the starting value (unity). The controlling quantity for the fuse resistance is the integral of the square of the current density in the wires. The integral of the square of the total current is often called the action integral and has a unit of Joules/Ω. The heating phase of the solid wires ends if the integral of the J^2 is equal to the so-called Blow Limit for the wire material. The value for copper for the parameter range in question is given by Equation 2. The value is slightly higher for faster current rise-times, but the variations are small.

$$BlowLimit_{Cu} := 1.63 \cdot 10^{8} \cdot amp^{2} \cdot sec \cdot cm^{-4} \qquad \text{Equation: 2}$$

Considering the given values for β and γ, the resistance of the wires has risen to 26 times the initial value at the beginning of the second (explosion) phase. Afterwards the resistivity is rising exponentially as shown by the second part of the definition in equation 1. At the transition point, the value of both functions is identical. A plot of the relative resistivity of the fuse wires is given in Figure 12.

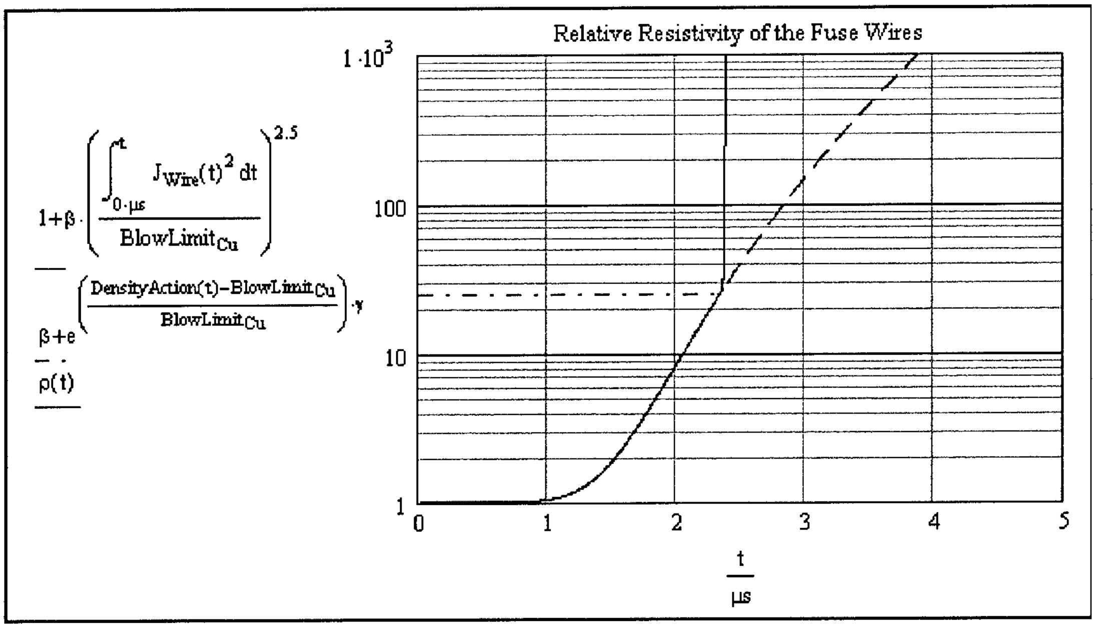

Figure 12: Plot of the relative resistivity given in Equation 1.

This model has been shown to produce results that correspond very well with our own and other's peoples experimental data.

Report on Subcontract # 1303/9073-01 to

MURI 98 Explosive–Driven Pulsed Power Generation

Paul Worsey, Professor and Jason Baird, Assistant Professor
University of Missouri–Rolla
Rolla, Missouri

Tests were performed by UMR personnel in support of TTU mechanical engineering staff research into armature metallurgic and high strain-rate effects during explosive events, as well as their investigations into ways of quantifying metallic surface electrical conductivity during explosive events.

A portion of the UMR research consisted of high-speed photographic investigation of armature expansion in visible wavelengths. To support this, and other efforts, a consumable flash illumination system to be used with the high-speed camera was completely designed and built, the first time that such a system was utilized for photography of this type.

A scheme was devised to catch armature fragments after subscale explosive events.

A hydraulic press system was designed and built to allow remote loading of armature explosives. Early on in the MURI project, consultations with researchers from the Phillips Laboratory and from LLNL and LANL resulted in a belief that this project would eventually require the loading of armatures with high explosives pressed to densities close to their theoretical maxima. Therefore, an explosives press design was undertaken and a press was built by UMR researchers. The press is capable of loading explosives into armatures remotely for personnel and facility safety, while being controlled by servo controls backed-up by pressure regulators and monitored by video.

High-speed photography of the expanding armatures shows no indication of the effects of voids in our hand-packed C-4 explosive charges (contrary to verbal predictions by National Lab personnel).

A gated image intensifier and associated digital camera (the combination will be referred to as an ICCD) were purchased utilizing other university funding, for use on this project.

UMR researchers performed energetic materials studies and tests of the influence of detonation waves on armature expansion and flux cut-off within generators. Jason Baird presented the results of his work on armature fractures and explosive void effects at the Pulsed-Power Plasma Science 2001 conference in July, was awarded his Ph.D. in August 2001, and assumed day-to-day responsibility for this project at that time. Paul Worsey was promoted to Professor status, and Mark Schmidt elected to pursue a Ph.D. with dissertation research appropriate to this project.

C-4 remained the primary test explosive, but different, higher performance explosives (HMX and PBXN-11) and lower performance explosives (dynamite, emulsion explosive)

were utilized for testing/live firing of test articles with the goal of examining the effects of detonation velocity and pressure on armature expansion, fracturing, and external Mach Stem formation. The use of HMX required remote-controlled loading of armatures, at up to 10,000 psi, in our Wombat underground facility.

Numerical modeling of the explosive/armature-tubing interface allowed for visualization of shock hydrodynamics during armature expansion. Baird's application of a two-dimensional Lagrangian shock hydrocode in his dissertation research allowed the modeling of shock interactions within armatures. Output of the model revealed the causes of processes that probably lead to flux cut-off during armature expansion.

Armatures were designed through the use of such codes, and then the armatures were tested to check their performance against the model predictions, with satisfactory results.

A series of multi-layered armature tests for Dr. Jahan Rasty (TTU Department of Mechanical Engineering) was completed. A test series was run utilizing polymeric inserts between explosive charge and armature, armatures with varied inside and outside surface finishes were test fired, a plane wave generator for strain wave testing in metals was designed. A test series with explosives of widely different detonation velocities was run.

A series of Aluminum/polymer armatures tests were fired and verified that small changes in density at material interfaces reduce surface cracking of armatures.

A test series on explosives void effects was completed; confirmed that near-surface explosives voids create "shaped-charge" penetration effect on armatures

John Walters (TTU) assisted in the adaptation, installation, and test of new Cordin camera digital controller in the UMR Explosives Research Lab. The adaptation was successful, thereby prolonging the life of our aging (ca. 1964) camera.

The construction/rehab of campus building (former US Bureau of Mines metallurgical research facility) as a new location for the Explosives Research Laboratory was initiated.

Report on Subcontract # 1303/3071-2 to

Explosive-Driven Pulsed Power Generation

Bruce Freeman, Research Professor
Dept. Nuclear Engineering
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Texas A&M University (TAMU) research has emphasized studies of the electrical properties of shocked gases under conditions approximating the interior of a flux compression generator, simultaneous and very small helical flux compression generators (FCG's), and initial development of appropriate loads for these smaller systems. A significant development at TAMU was the creation of an explosive test capability, at minimal cost to the MURI program. The studies of the electrical state of the gases within the interior of the explosive generators has lead to some practical rules of thumb for determining when to use enhanced dielectric gases, as opposed to either normal atmospheric air or dry air. The small helical generators will allow us to examine the issues that are involved with the very small FCG's. The simultaneous helical generators may offer the possibility of designing an explosive pulsed power system that incorporates the FCG and pulse forming line as an integral unit. As part of the advanced generator development, we have begun to incorporate non-passive loads into our testing to examine the effects on the FCG systems. Particularly in the last year, we have been involved with DoD partners and contractors, due at least in part to our continued participation in the MURI.

TAMU Facilities

At the beginning of the MURI program, we located an abandoned, man-rated, diving vessel and moved it to the Riverside Campus of Texas A&M University. This vessel underwent a study by the Los Alamos National Laboratory that indicated the vessel would be capable of safely withstanding an explosive load of 30 pounds, or greater, in a closed configuration. The rating assigned to this vessel, by us, in an open configuration is only 3 pounds of explosive, which is greater than a factor 20 below the Los Alamos study. We installed the vessel next to our diagnostic/control trailer on insulated pads to provide for a single-point-ground configuration. Along with this firing capacity, we have a large storage magazine and a local storage vault to support ongoing explosive development and operations.

Research Areas

Electrical Properties of Shocked Gases

Gases located between the stator and armature of a functioning FCG will be highly compressed and shocked as the armature completes its run near the time of generator burnout. Thus, the characteristics and behavior of such gases, which are also subjected to the internal voltages of the FCG, may have a significant impact on the final performance of the device. Quite frequently the ambient air is simply displaced with sulfur hexafluoride (SF_6). This is a relatively dense and strongly electronegative gas. Nevertheless, the electrical properties of SF_6 under conditions present within a functioning FCG have never been measured and, being a heavy gas, the use of SF6 will result in slower armature velocities.

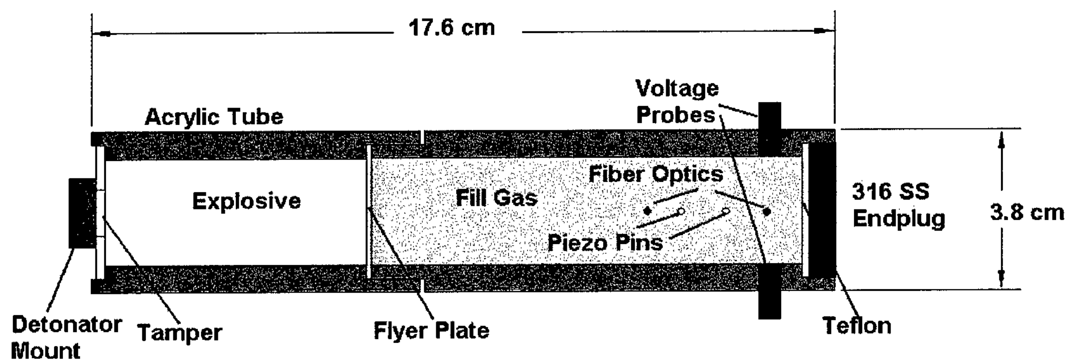

Figure 1: Sketch shows the construction of the shock tubes used for the gas conductivity studies.

Experiments using helium, argon, synthetic air, and sulfur hexafluoride as the working gases have been performed using the shock tube design shown in Fig.1. The helium tests were intended to provide a comparison with earlier Russian experiments. The argon tests should have provided early and substantial conductivity measurements from the shock process and did. The synthetic air and SF6 tests were intended to provide the explosive generator community with a direct comparison between these two gases as working fluids within functioning generators. Generally, SF6 is indeed a better insulator than the synthetic air, but synthetic air results in about a 10% faster velocity of the metal flyer plate, the armature simulant. Therefore, in situations that will challenge the insulation capabilities of the generator, one is generally advised to replace the ambient gases in the working volume with SF6. Under less demanding conditions, the use of atmospheric air or synthetic air, for more controlled conditions, is recommended since the armature performance is not impeded by the heavier gas.

Initial Helical Generator Design

Preliminary design of a first MURI helical generator (TTU-1) was completed to provide a testbed for concepts and understanding within this MURI program. We collaborated with Prof. M. Kristiansen and Dr. A. Nueber (TTU) and Drs. C. M. Fowler and William

Deninger (LANL) in this effort. SCAT95 calculations of this design were provided in advance of the explosive tests conducted.

Simulation of TTU-2 Generator Using SCAT95

We accepted the challenge to provide simulations for a second generator, TTU-2, in advance of the testing of this design. Extensive, parameterized simulations were necessary to obtain the requested calculated results. A comparison of the experimental data with the simulations revealed that the TTU-2 generator had excessive losses at low initial currents that lead to very much lower gains than predicted. For final currents up to about 100 kA, the gain predicted by SCAT was well matched with the experimental data. Beyond this level of performance, the SCAT simulations progressively departed from the experimental data.

Small Generator Design and Testing

For several years, the DoD community has wanted to see how small flux compression generators could be made and still achieve reasonable performance. This need was strongly emphasized at the IEEE PP/PS conference in June 2001. After this conference, we decided to pursue this avenue of research vigorously. The reasons for this were several. First, the DoD community has expressed a pressing need to have research of this nature performed. Second, we had two undergraduate students and one graduate student who were interested in this area of study. Third, the smaller systems are easier in many respects to fabricate and test.

For the initial tests, the characteristic dimensions for the generator design were an armature external diameter of 1.27 cm and a stator internal diameter of 2.54 cm, Fig. 2. The initial magnetic field was provided by two neodymium-iron-boron permanent magnets.

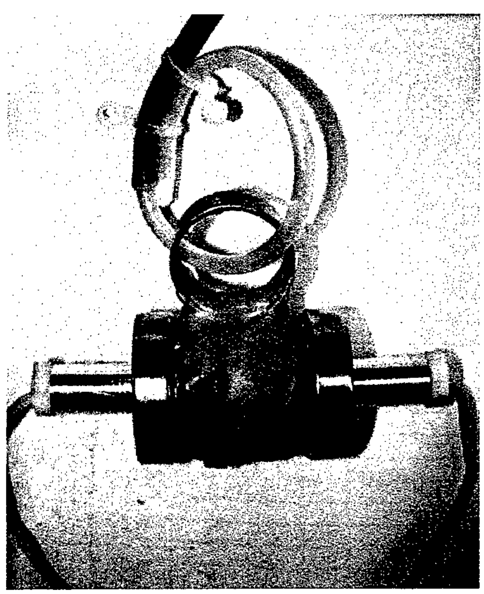

Figure 2: Pictures of the TAMU Mark I generator.

The magnetic field at the pole faces of these magnets was about 12,000 gauss. A serious consideration is that only the field components that can be supported by the generator winding will be trapped once the shock wave destroys the permanent magnets. Given that the field structure near these disk magnets was highly divergent, relatively little of the initial magnetic field was useful for the generator. Nevertheless, maximum currents and voltages of 2.1 kA and 150 V were measured for a load inductance of ~5 nH.

The Mark II generator design replaced the permanent magnet seed source with a capacitor feed while retaining the same dimensions (IIA) and the double-ended initiation Fig 3. Once the initial experiments were completed, we extended the stator of the Mark II to a length of 5 cm to increase the generator gain and provide a larger working volume (IIB). In total, six of this style generator was tested. Typical initial currents were ~200 amperes and final currents ranged from ~800 to 2,500 amperes. We observed significant flux loss and decreased generator performance with the Mark II units from the cutting action induced by the meeting of the opposing detonation waves. Earlier work addressed this problem by inserting an inert material at the center of the armature to avoid having the detonation waves interact directly. Case motion studies are required to moderate this interaction before continuing the use of this design.

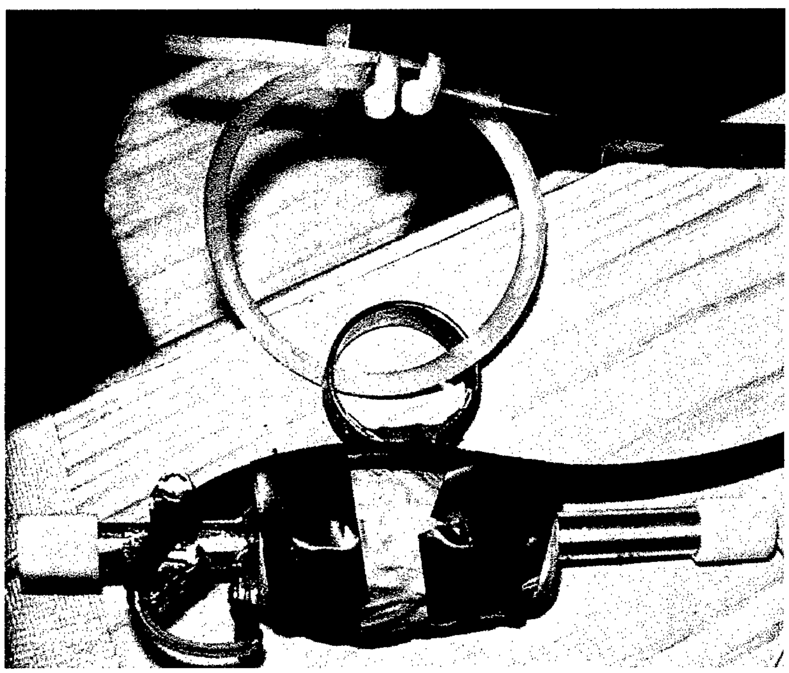

Figure 3: Mark IIB generator ready for testing.

The Mark II generator was redesigned to a smaller form factor (armature diameter) and again seeded from a capacitor source. The double-ended initiation was replaced with single end initiation because of armature cutting in the central plane. The Mark III has a form factor of about 2.54-cm outer diameter, Fig 4. The nominal armature outer diameter is 0.94 cm, and the stator inner diameter is 1.905 cm. This generator design is the one that was tested most through the year's research, with 12 units fired. The armature wall

thickness was thinned from ~0.889 mm to units with a wall thickness of only 0.508 mm. Toward the lower end of this range, we appear to have realized a Gurney angle for C-4 of about 16° for this geometry.

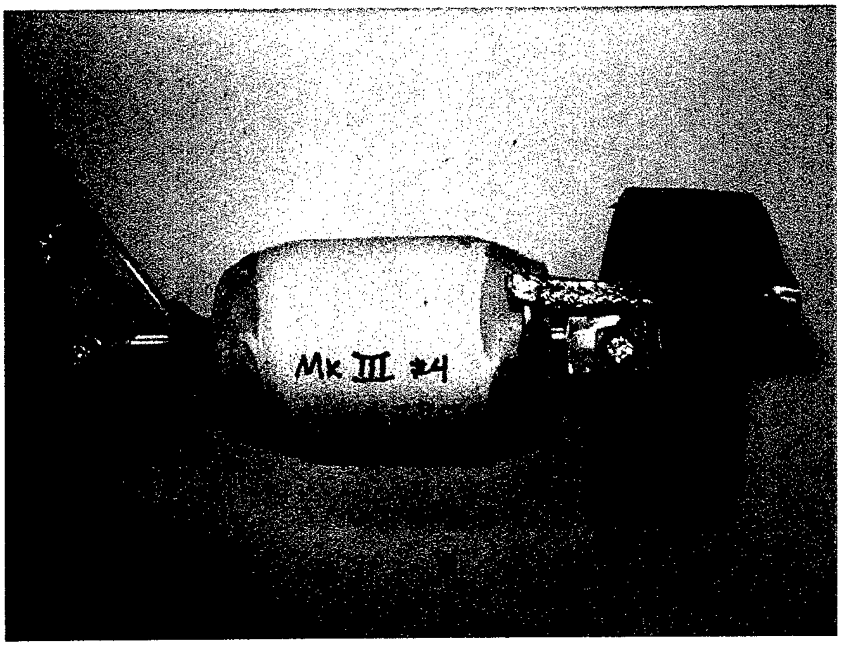

Figure 4: The fourth Mark III to be tested shows both the initiation and feed for seed current.

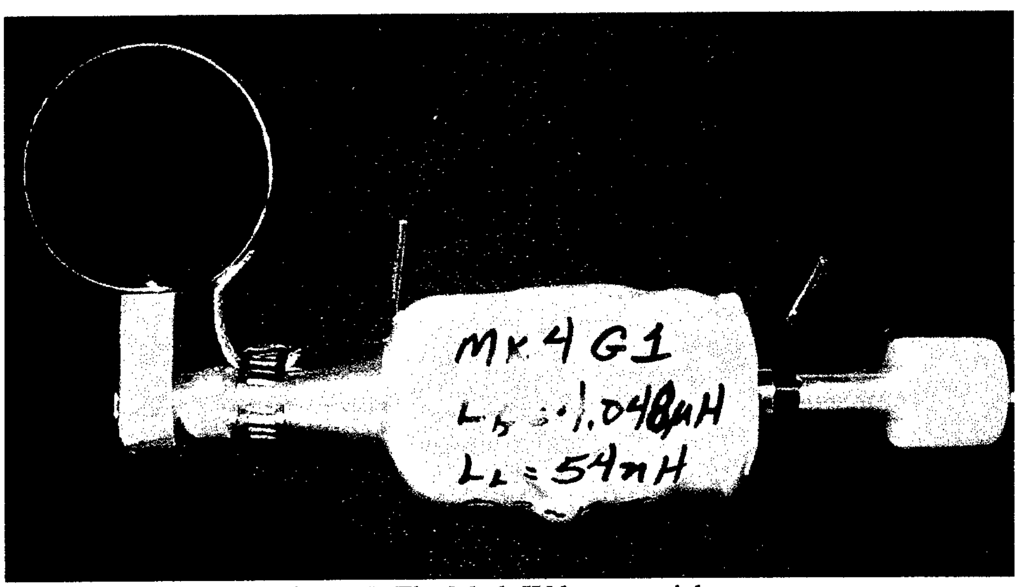

Figure 5: The Mark IV has an axial output.

Through the initial designs of these small FCGs, the output end of the generator has been located at the stator radius. The Mark IV generators moved the output of the generator to the armature axis. To accomplish this design while retaining the very small form factor, the output glide plane was reduced to a cone shape, Fig. 5. All other dimensions were carried over from the Mark III design. Unfortunately, the output cone proved to be difficult to center properly. Both tests of this geometry have demonstrated a lack of centering and turn skipping.

The Mark V generator design is a larger form factor than previously tested (Fig. 6). The outer diameter of the armature is 2.54 cm, and the inner diameter of the stator is about 4.57 cm for a 2:1 expansion ratio. The stator length is 6.96 cm, which is about 2 cm longer than the earlier systems. Also, the mass of C-4 explosive in the armature is significantly more than the earlier FCGs at ~90 grams.

Figure 6: The Mark V generator has a form factor of about 6 cm after potting.

The Mark 100 FCG is a tapered stator generator where the taper is set at a conservative 10°, Fig. 7. This assured that the armature would not close the output before progressively contacting the outer stator windings. The purpose of this generator design is to raise the dL/dt of the unit by making the contact of the armature with the stator more simultaneous. The outer diameter for the armature of this FCG is 2.54 cm. The stator ranges from 5.02 cm to 2.65 cm over a length of 6.985 cm.

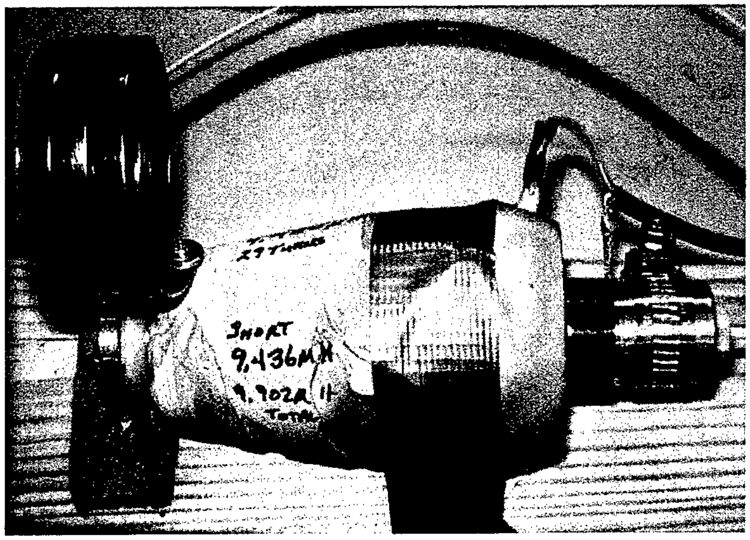

Figure 7: The 10° tapered stator Mark 100 has provided higher performance.

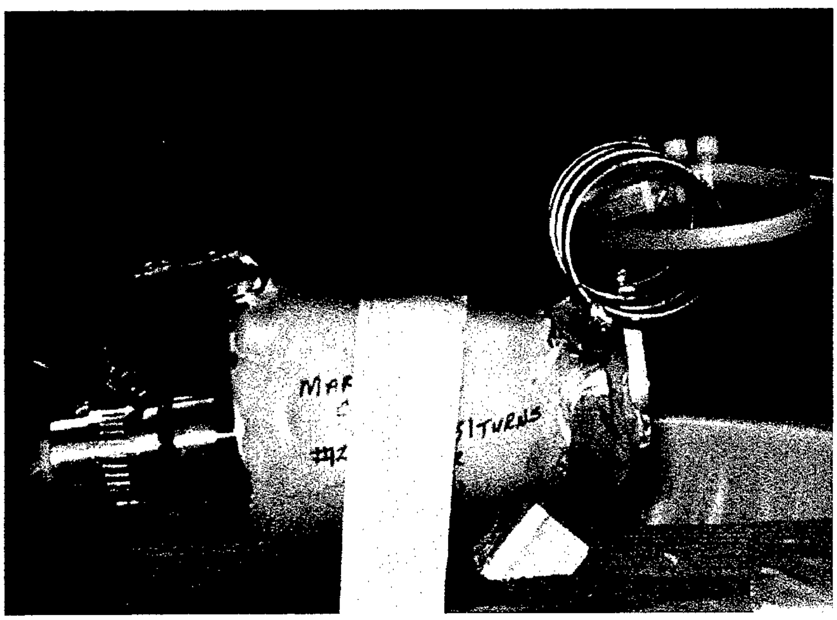

Figure 8: The Mark 101 with its 12° tapered stator has provided the best performance of all designs.

The Mark 101 generator design employs a 12° tapered stator to raise further the dL/dt of the system, relative to the Mark 100's 10° taper (Fig. 8). The armature in this generator has essentially the same dimensions as the Mark 100. The stator varies from 5.51 cm to 2.65 cm, which results in more that a factor of two in armature expansion in the input end of the taper. In all of the shots fired with this design, the system performed well, so the 12° taper appears to be relatively conservative as well.

Extending the development of the Mark 101 generator, the Mark 103 helical generator used a 13° taper angle to raise its effective closure phase velocity, Fig 9. The construction of this FCG required improvement of our fabrication techniques to insure that clocking and turn skipping were minimized. In this model, we expanded the armature slightly to have an inner diameter of 2.54 cm. The armature wall thickness was also reduced to 0.76 mm. For the second test of the Mark 103 generator design, the initial FCG inductance was 16.07 μH, and its passive load inductance was 30 nH.

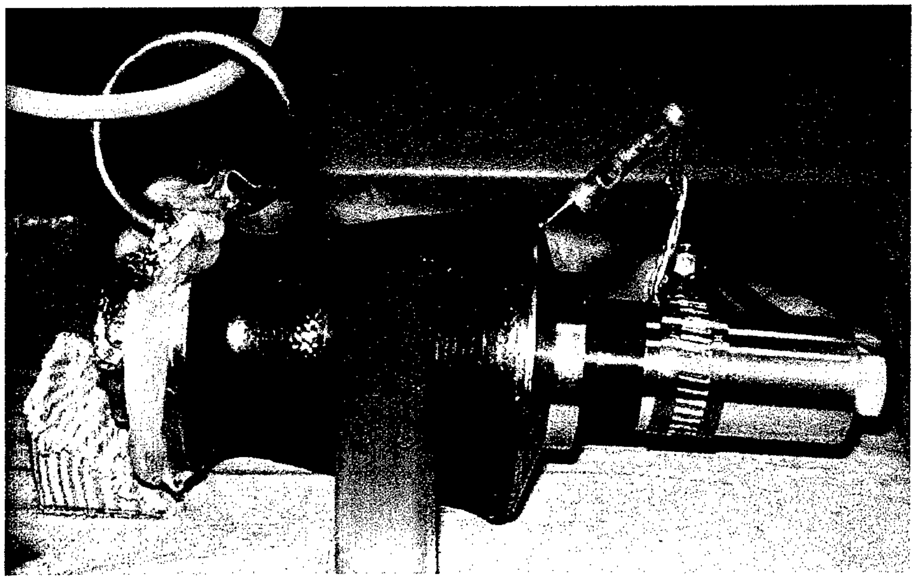

Figure 9: The Mark 103 uses a 13° taper angle and delivers the highest peak dI/dt and power outputs of any of our other generator designs.

The second test of the Mark 103 had a very high ideal gain, which leads to a lower expectation for α. (α is the experimental current gain divided by the theoretical gain.) Nevertheless, the distinguishing characteristic for the test is that the current derivative or dI/dt trace indicated the cleanest generator performance that we have observed in the small systems (Fig. 10). The initial current was 912 A, and the final current was 20.73 kA. Thus, the current gain was 22.7:1, but the α was only 0.497. The associated energy gain was also less than unity, as anticipated, at 0.96:1. The more important point is that the FWHM of the dI/dt pulse was reduced to 398 ns. The peak load voltage was about 1.09 kV, and the maximum instantaneous power delivered to the load was 28.7 MW, with a FWHM value of ~250 ns (Fig. 11). Using the current and voltage results, the effective generator impedance was ~53 mΩ. Given the process that is used for this part of the analysis, the lack of flux pocketing indication on this trace is very surprising.

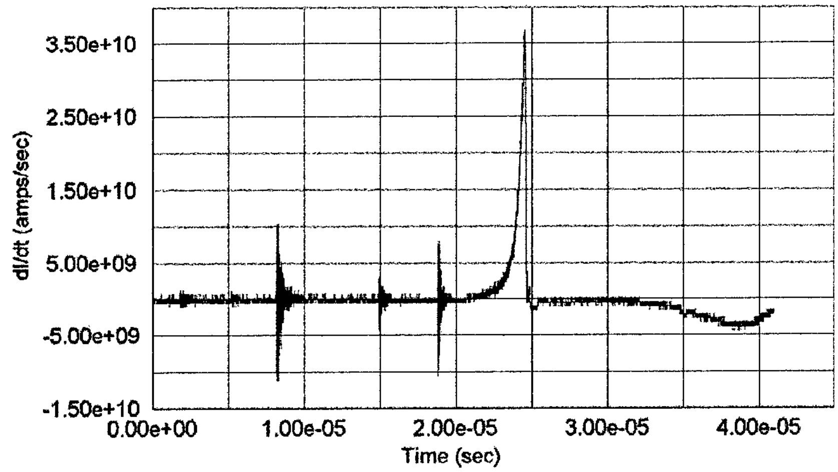

Figure 10: The time history of the current time derivative is plotted for the Mark 103 Test #2. The very clean rise of the pulse is a good indication of a very good axial alignment between the stator and the armature.

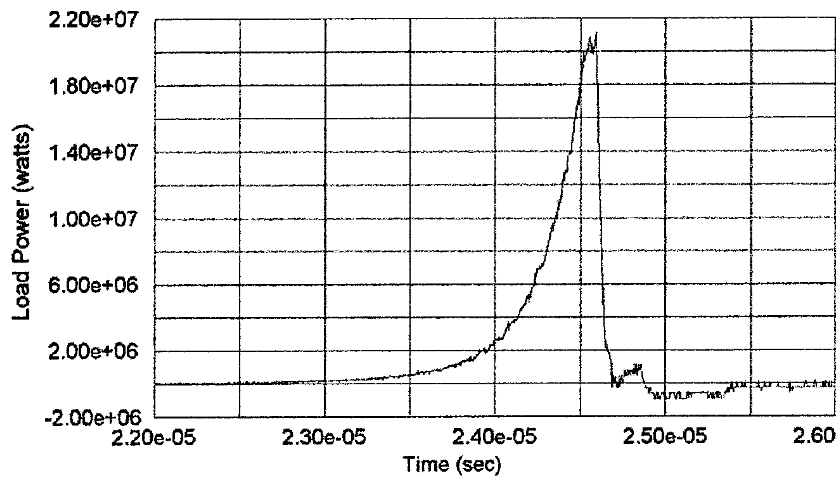

Figure 11. Using the same expanded time scale as for Fig. 8, this plot illustrates the time history of the power delivered to the load inductor for the Mark 103 Test #2.

The Mark 102 FCG design adds a helical gain section to the 12° taper stator of the Mark 101. Thus, the stator length is extended to 9.53 cm, with a corresponding explosive mass increase to ~140 grams of Composition C-4. The initial generator inductance was measured to be about 21 μH. This compares with the initial inductance of a Mark 101 with #12 magnet wire of 11.2 μH. Thus, the Mark 102 contains about 10 μH in the straight helical section before the tapered section. The initial testing for this generator design was not encouraging because it exhibited excessive clocking. However, the fabrication techniques used for the Mark 103 were not used for the initial units of this FCG model.

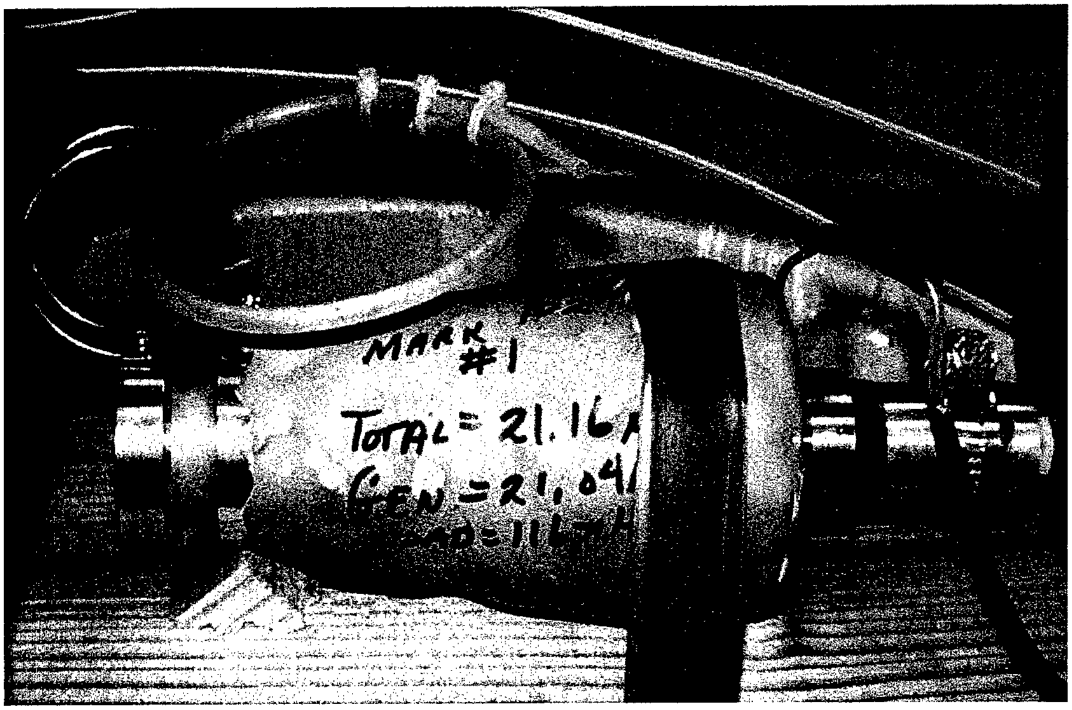

Figure 12: The Mark 102 has a short helical gain section added to the basic Mark 101.

Simultaneous Generator Design

Simultaneously initiated generators have long been recognized as a means to significantly enhance FCG performance with existing explosives. This is particularly true for simultaneous helical designs. For example, the progressive explosive-burn helical generator may have a maximum dL/dt in the range of ~10 mΩ, but a simultaneous helical FCG may be designed to have maximum dL/dt's in the range of 0.1 to 10 Ω. An example of a generator designed to present ~ 25mΩ source impedance to a high current load is shown in Figure 13.

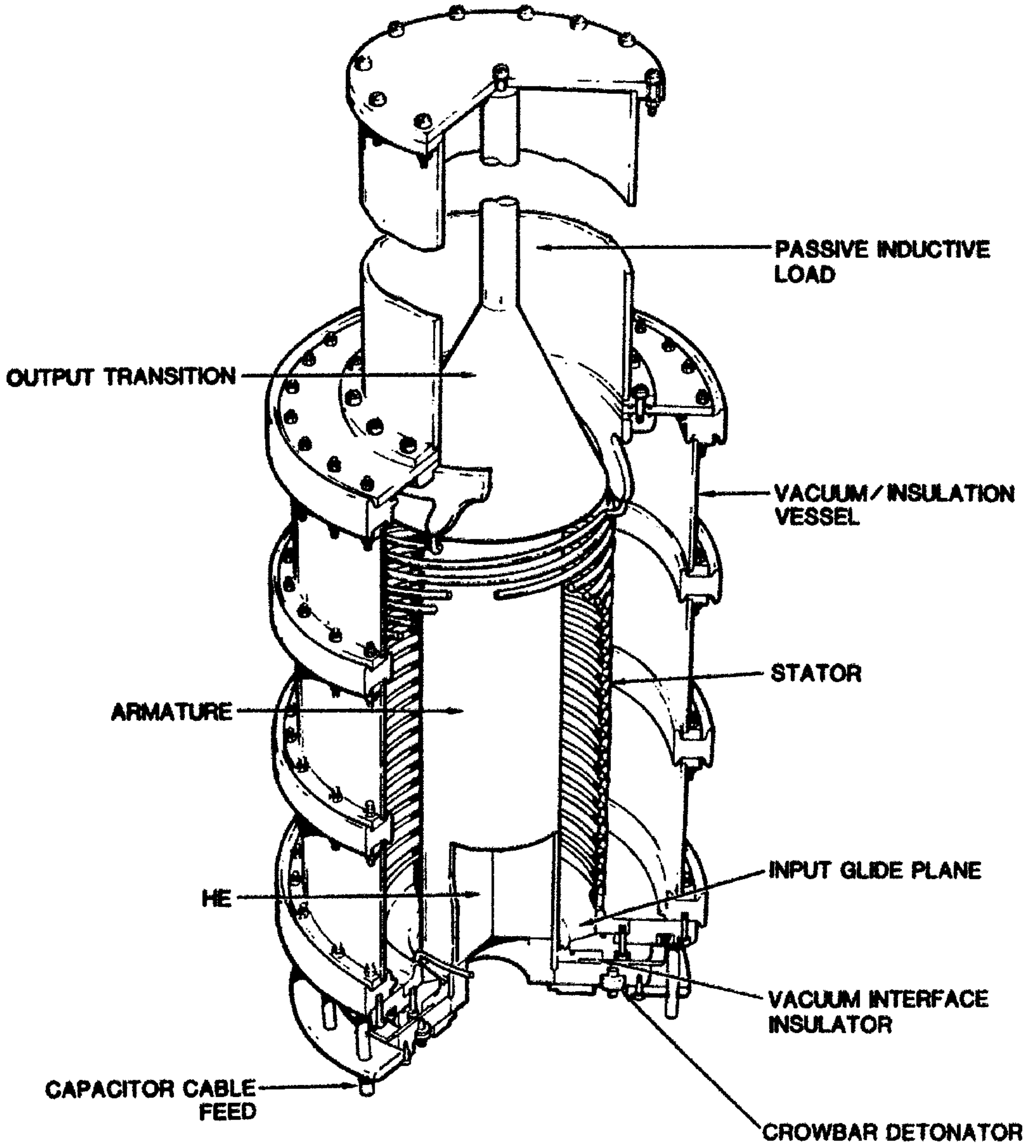

Figure 13: LANL Mark 101 simultaneous helical flux compression generator is shown in cut-away sketch.

Research effort in this area was significant during the later 1980s, but these studies have been largely discontinued at the present time. A significant reason for the cessation of research in this area is the lack of affordable areal (simultaneous ignition over an area) explosive initiation systems. Nevertheless, the promise of simultaneous generators is that

one can design much of the performance needed for various loads into the generator geometry, thus lessening the demands either for or on the pulse forming network.

Toward this end, we have studied how these generators may be used with known loads for the FCG's. A key issue of this study was to see how affordable initiation systems may be developed to enable a new effort to research the capabilities and limitations on this generator design. To this end, we have been discussing the possibilities of a joint effort with PANTEX for initiator development. We are also developing modeling capability to enable simulation of this class of generator. An example of this modeling is shown in the modeling of the simultaneous helical generator, reported by Caird and Fowler in the 4^{th} *International Megagauss Conference* (Fig. 14).

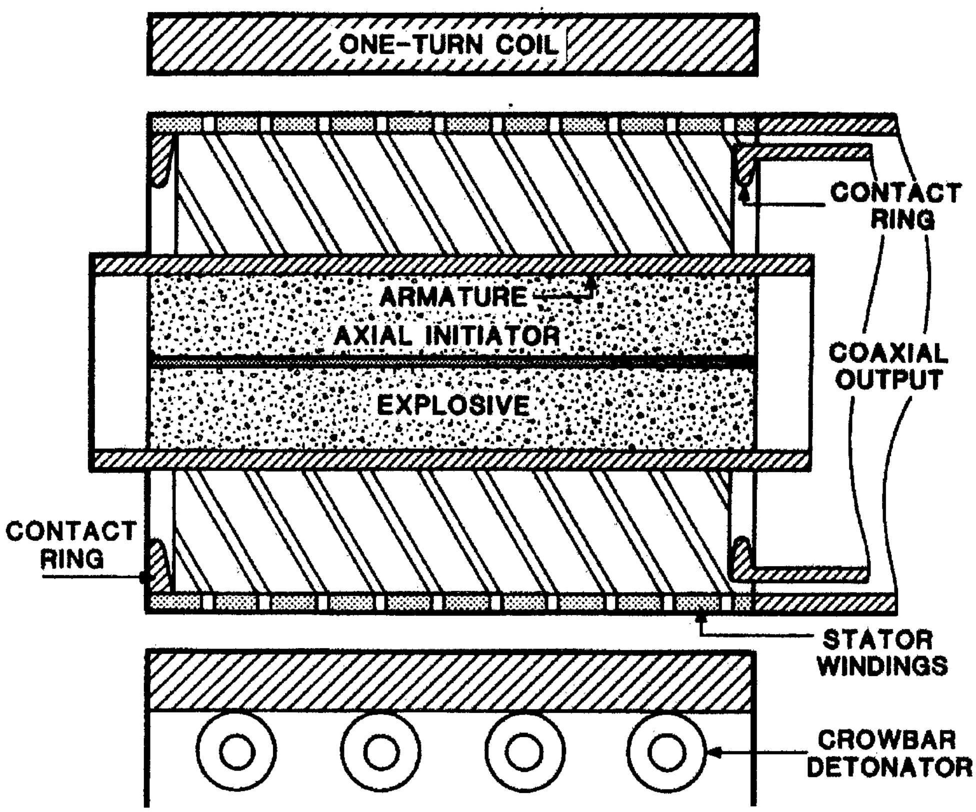

Figure 14: Simultaneous helical generator design that has no current output until it is switched to its load.

Application of Small Helical FCGs to RF Generation

During that last few months of the MURI, we performed several experiments to study the application of a Mark 101 generator to power a ferrite-loaded, double tank circuit to produce RF frequencies as an ultra wide band source. The circuit used is shown in Fig. 15. The exact values are not shown in the circuit because we were varying these to optimize the resulting data from the tests. In all of the tests, the inductors on the ferrite

core had vacuum inductances of about 30-40 nH. For the second generator-powered test, the high frequency tank capacitance was 48 pF, and the low frequency tank capacitance was 1.2 nF. The resistive load was 155 ohms.

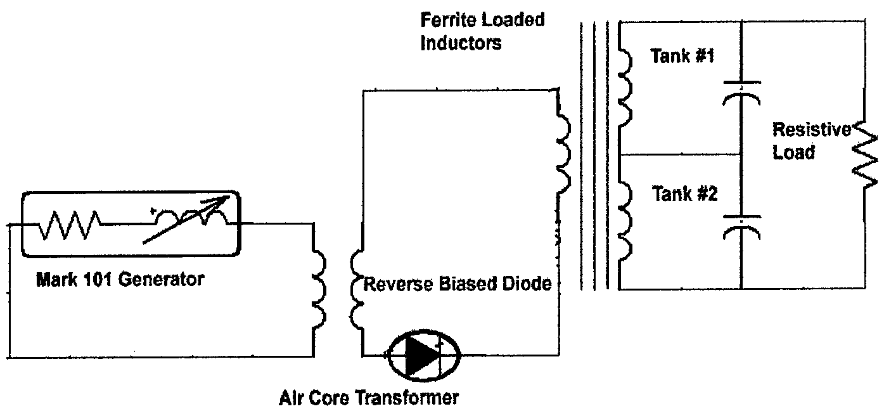

Figure 15: The circuit schematic shows the general configuration for the double tank circuit that was tested using Mark 101 FCGs to drive the system.

Figure 16 shows the physical layout of the experimental configuration before the generator was fired. The Mark 101 generator, on the left side of the picture, is connected to a 10:1 air core transformer using a very low inductance connection. The coupling coefficient of the air core transformer was ~0.92. The air core transformer, in turn, is coupled to a single turn on the 3C8, 2.54-cm square ferrite using a back-biased diode that provides a ≥1 kV threshold closing switch. Each of the two low inductance inductors, ferrite saturated, for the tank circuits are also coupled off the ferrite ring.

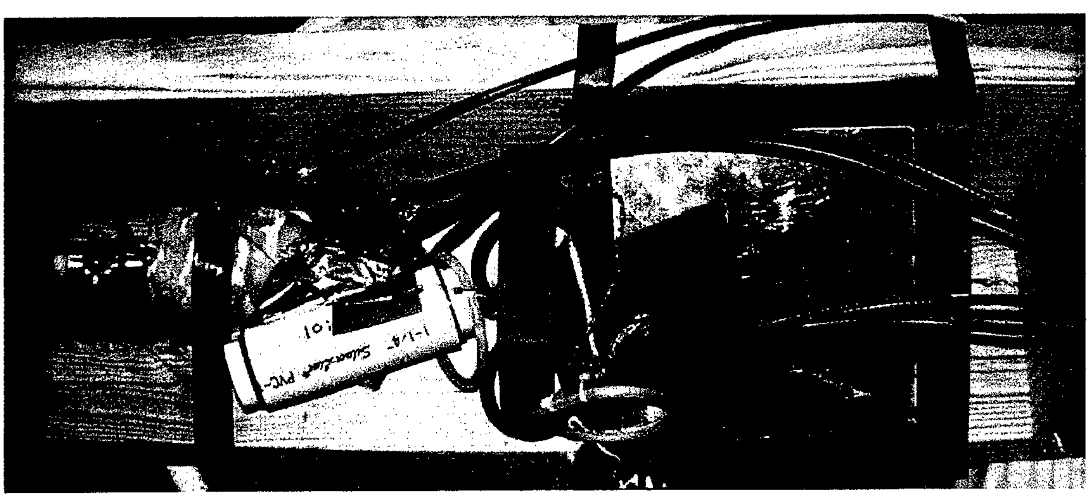

Figure 16: Photography shows the physical configuration of the second test of a generator-powered double tank circuit before the experiment was fired.

The capacitors were fabricated locally to provide both a high voltage insulation capability and a relatively high Q for their circuits. The results of this test are indicated by the waveform shown in Fig. 17. The over-voltage switch in the secondary of the air core transformer activates at about 37 μs. A second distinct oscillation, that starts at ~38.5 μs, is the time when the voltage on the drive winding of the ferrite reverses polarity. Close examination of this waveform indicates frequency components from ~50 MHz to ~250 MHz. Given the sampling rate of the digital recorder, the higher frequency is suspect and requires a better measurement. From the modeling work performed before these experiments were fired, we conclude that the Atherton-Jiles model for magnetic materials does not provide a sufficiently complete understanding to enable adequate interpretation for the data obtained. More study of both the saturable materials models and the experimental configuration is required before we have a scaling understanding of this phenomenon.

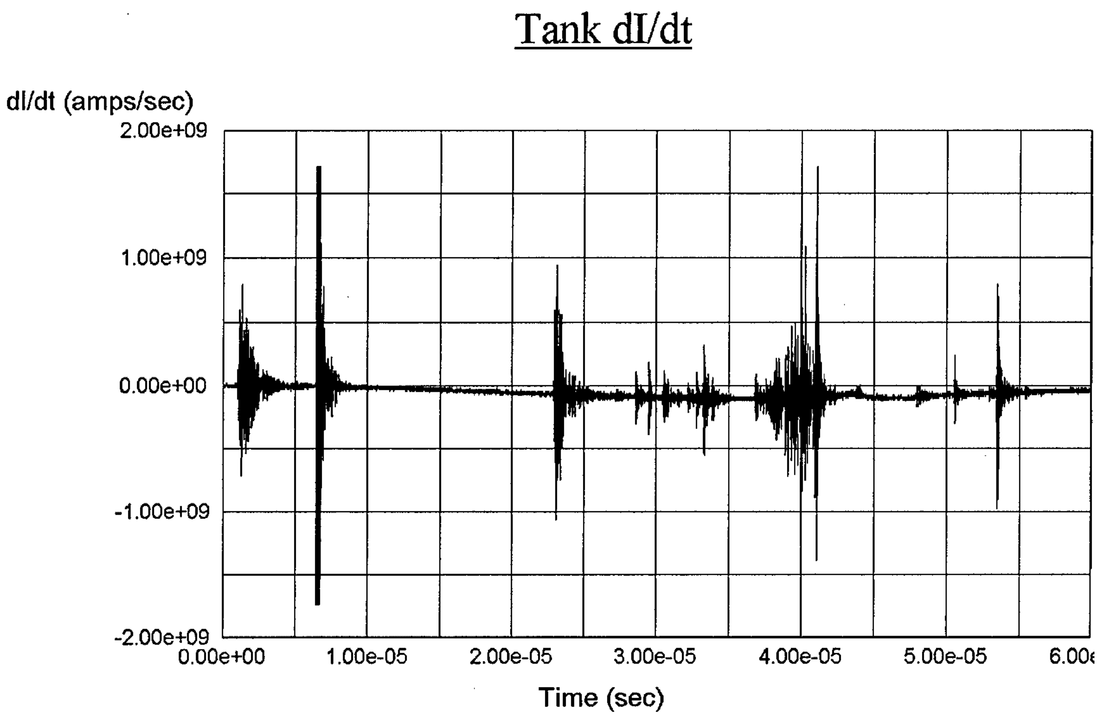

Figure 17: The waveform shows the performance of the double tank circuit as measured across the resistive load resistor. The measurement is physically made using a small Rogowsky loop.

Graduate Students

TTU

Thomas Holt, (MS),	Naval Research Laboratory.
Nathan Schoeneberg (MS)	SAIC
Tammo Heeren, (Ph.D.)	Visiting Assoc. Prof., Kumamoto University, Japan
Gin Gi Kim, Ph.D.	Research Scientist, Kwangwoon University, Seoul, Korea
David Hemmert, Ph.D.	President of HEM Technologies/Post Doctoral Student at TTU
Xiaobin Le, Ph.D	With a Material Science Company in Toronto, Ontario, Canada
Juan-Carlos Hernandez, Ph.D.	Finishing Ph.D. (August 2004)
Branden Dixon, MS	TTU M.S. Student

UMR

Jason Baird (Ph.D)	Assist. Research Prof, Rock Mechanics and Explosive Research Center, University of Missouri-Rolla
Mark Schmidt (MS)	Ph.D. Student, University of Missouri-Rolla

TAMU

D. J. Dorsey (MS)	LANL
John Boyston, MS	Completing his thesis at TAMU

Undergraduate Students

Some 20 undergraduate students at the 3 universities at one time or the other worked on the program

PUBLISHING ACTIVITIES

Journal Articles

1. J. Rasty, X. Le, J. Dickens, A. Neuber, J. Mankowski, D. Hemmert, M. Kristiansen, J. Baird, M. Schmidt, and P. Worsey, "Design Criteria for Prevention of Armature "Turn-Skipping" in Helical Magnetic Flux Compression Generators", Submitted to Journal of Applied Physics, September 2003.

2. J. Rasty, X. Le, A. Neuber, J. Dickens, J. Zhang, J. Mankowski, D. Hemmert, and M. Kristiansen, "Electrical Conductivity of Oxygen-Free High-Conductivity Copper Under Conditions of Shock and High Strain-Rate Loading" Submitted to ASME Transaction, Journal of Engineering Materials and Technology (JEMT), July 31, 2003.

3. J. Rasty, X. Le, L., Murr, J. Dickens, A. Neuber, J. Mankowski, D. Hemmert, M. Kristiansen, J. Baird, M. Schmidt, and P. Worsey, "Micro-Structural Evolution of the Armature Material Subjected to Explosive Shock-Loading in Magnetic Flux Compression Generators." In preparation for submission to the Journal of Applied Physics.

4. M. Giesselmann, T. Heeren, E. Kristiansen, J. Kim, J. Dickens, M. Kristiansen, "Experimental and Analytical Investigation of a Pulsed Power Conditioning System for Magnetic Flux Compression Generators", IEEE Transactions on Plasma Science, October 2000, Vol. 29. 1368-1376

5. A. Neuber, J. Dickens, J. B. Cornette, K. Jamison, R. Parkinson, M. Giesselmann, P. Worsey, J. Baird, M. Schmidt, and M. Kristiansen, "Electrical Behavior of A Simple Helical Flux Compression Generator for Code Benchmarking", IEEE Transactions on Plasma Science, Vol. 29, No. 4, August 2001.

6. M. Giesselmann, T. Heeren, A. Neuber, J. Walter, M. Kristiansen, "High-Speed Optical Diagnostic of an Exploding Wire Fuse", IEEE Transactions on Plasma Science, Vol. 30, No. 1, February 2002, p. 100...101.

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8. P. N. Worsey, J. Baird, and M. Schmidt, "Maximizing Resolution of the High-Speed Photography of Explosive-Driven Power Generator (EDPG) Armatures in Operation", published in the IEEE Transactions on Plasma Science.

9. Baird, J. and P.N. Worsey, “The Causes of Armature Surface Fracturing Within Helical Flux-Compression Generators,” IEEE Transactions on Plasma Science Special Issue on Pulsed-Power Science and Technology, 30, 1647 (2002).

10. Baird, J., “Explosive Shocks and Impedance Mismatch in Armatures,” to be published in the European Journal of Electromagnetic Phenomena late 2003/early 2004.

11. Bruce L. Freeman, Larry L. Altgilbers, Alvin D. Luginbill, and James C. Rock, “Development of Small, Tapered Stator Helical Magnetic Flux Compression Generators,” Submitted to the Journal of E&M Phenomena, 2003.

12. Bruce L. Freeman, Larry L. Altgilbers, C. Maxwell Fowler+++, and Alvin D. Luginbill, “Similarities and Differences Between Small FCG’s and Larger FCG’s,” Submitted to the Journal of E&M Phenomena, 2003.

13. D. Dorsey and B. Freeman, "Comparison of Sulfur Hexifluoride and Synthetic Air in a Simulated Flux Compression Generator Environment," IEEE Transactions on Plasma Science, Vol 29, No. 5, pp. 815-819, October, 2001.

14. A. Neuber, J. Dickens, H. Krompholz, and M. Kristiansen, “Optical Diagnostics on Helical Flux Compression Generators”, IEEE Trans. on Plasma Science, vol. 28, 1445-1450 (2000).

15. A. Neuber, J. Dickens, J. B. Cornette, K. Jamison, R. Parkinson, M. Giesselmann, P. Worsey, J. Baird, M. Schmidt, and M. Kristiansen, “Electrical Behavior of a Simple Helical Flux Compression Generator for Code Benchmarking,” IEEE Trans. on Plasma Science, vol. 29, 573-581 (2001).

16. A. Neuber, J. Dickens, M. Giesselmann, M. Kristiansen, B. Freeman, D. Dorsey, P. Worsey, J. Baird, and M. Schmidt, “Studies on a Helical Magnetic Flux Compression Generator,” SAE Transactions, Journal of Aerospace, vol. 109, pp. 865-869, 2000 (This Transactions volume was published in 2001 and “…contains the best 135 technical papers of all those presented in 2000.”).

17. A. Neuber, T. Holt, J. Dickens, and M. Kristiansen, “Thermodynamic State of the Magnetic Flux Compression Generator Volume,” IEEE Trans. on Plasma Science, vol. 30, 1659-1664 (2002).18.

18. Andreas A. Neuber, Juan-Carlos Hernández, James C. Dickens, Magne Kristiansen, ”Helical MFCG For Driving A High Inductance Load,” accepted for publication in the Special Edition of the Journal of EM Phenomenon on FCGs (Oct. 2003).

19. Bruce L. Freeman, Larry L. Altgilbers, Alvin D. Luginbill, and James C. Rock, “Development of Small, Tapered Stator Helical Magnetic Flux Compression Generators,” Electromagnetic Phenomena, Vol. 3, #3, (11), 2003.

20. Bruce L. Freeman, Larry L. Altgilbers, C. Maxwell Fowler, and Alvin D. Luginbill, "Similarities and Differences Between Small FCG's and Larger FCG's," Electromagnetic Phenomena, Vol. 3, #3, (11), 2003.

21. Dorsey and B. Freeman, "Comparison of Sulfur Hexifluoride and Synthetic Air in a Simulated Flux Compression Generator Environment," IEEE Transactions on Plasma Science, Vol 29, No. 5, pp. 815-819, October, 2001.

Conference Proceedings

22. David Hemmert, John Mankowski, Jahan Rasty, Andreas Neuber, Xiaobin Le, James Dickens, and Magne Kristiansen, "Conductivity Measurements of Explosively Shocked Aluminum and OFHC Copper Used for Armature Material in a Magnetic Flux Compression Generator," 14th IEEE International Pulsed Power Conference Proceedings, Dallas, Texas, June 16-18, 2003.

23. Jahan Rasty and Xiaobin Le, James Dickens, Andreas Neuber, and Magne Kristiansen, "Design Criteria for Prevention of Armature Turn-Skipping in Helical Magnetic Flux Compression Generators," 14th IEEE International Pulsed Power Conference Proceedings, Dallas, Texas, June 16-18, 2003.

24. Rasty, J., Le, X., Neuber, A., Dickens, J., Kristiansen, M. "Microstructural Evolution of the Armature Material Subjected to Explosive Shock Loading in Magnetic Flux Compression Generators," The Ninth International Conference on Megagauss Magnetic fields Generation and Related Topics, Moscow-St. Petersburg, Russia, July 7-14, 2002.

25. Le, X., Rasty, J., Neuber, A., Dickens, J., Kristiansen, M. "Effect of Scaling on the Armature's Expansion Angle in Magnetic Flux Compression Generators," The Ninth International Conference on Megagauss Magnetic fields Generation and Related Topics, Moscow-St. Petersburg, Russia, July 7-14, 2002.

26. Rasty, J., Le, X., Neuber, A., Dickens, J., and Kristiansen, M. "Experimental and Numerical Investigation of the Armature/Stator Contact in Magnetic Flux Compression Generators," Proceedings of the 28th IEEE International Conference on Plasma Science, Las Vegas, Nevada, June 17-22, 2001.

27. Le, X., Rasty, J., Neuber, A., Dickens, J., and Kristiansen, M., "Calculation of Air Temperature and Pressure History during the Operation of a Flux Compression Generator," Proceedings of the 28th IEEE International Conference on Plasma Science, Las Vegas, Nevada, June 17-22, 2001.

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The consortium is currently drafting a handbook on Helical Magnetic Flux Compression Generators, in which we will summarize the findings (operating principle, basic physics, design guidelines, etc.) of this MURI program.

SIGNIFICANT INTERACTIONS

- Numerous discussions with and delivery of experimental results and presentations to US Army SMDC
- TTU and TAMU delivered approximately 40 experimental devices to NAVAIR at China Lake
- TTU and TAMU presented short courses "Magnetic Flux Compression Generators" to NAVAIR personnel at China Lake
- TTU and TAMU carried out experimental demonstrations for industrial customer (TTU work still on-going)
- TAMU interacted extensively with LANL personnel, esp. Dr. M. Fowler
- TTU interacted extensively with the group at Loughburough University in England (Dr. Ivor Smith) and exchanged experimental information. TTU visited LU and LU carried out computer calculations for TTU
- TAMU carried out discussions with PANTEX personnel about joint experiments utilizing PANTEX facilities and detonator technology. Discussions were also held between PANTEX and TTU.
- J. Dickens and M. Kristiansen presented a lecture on explosive flux compression generators at Monterey, CA.
- A. Neuber Traveled to General Atomics, San Diego, CA, December 4th -6th, 2002. Presented an overview of Explosive Pulsed Power/Magnetic Flux Compression for HPM to the CEO and technical people at GA.
- The University of Texas at Austin Institute of Advanced Technology carried out computer simulations for TTU.
- Dr. Murr, The University of Texas at El Paso, carried out metallurgical analyses for TTU.
- Dr. Worsey visited Dr. I. Smith of the Department of Electronic and Electrical Engineering, Loughborough University in Loughborough, UK, 8 – 14 January 1999. Drs. Worsey and Smith discussed EDPG design, and Dr. Worsey toured the Loughborough Pulsed-Power Generation facilities.
- UMR hosted a visit by Dr. I. Smith of Loughborough University, 6 – 9 July 1999. Dr. Smith toured the UMR facilities, participated in EPDG design discussions, and presented a tutorial on novel flux compression techniques.
- Dr. Goforth, LANL, enabled the casting of surplus PBXN-11 explosive into UMR MURI armatures at the Navy's China Lake facility. The armatures will be used in tests at UMR.